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ASD-TDR-62-975

Turbojet Engine Analyzer Design Study

406 348

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-62-975

April 1963

Check-Out and Test Equipment Division
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 3147, Task No. 314702

(Prepared under Contract No. AF 33(616)-8508
by General Electric Instrument Department
West Lynn, Massachusetts.
Authors: M. E. Douglass et al.)

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Unclassified Report

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FOREWORD

The work covered by this report was undertaken by the Instrument Department of the General Electric Company in response to Purchase Request #122701 initiated by the Aeronautical Systems Division, Air Force Systems Command, United States Air Force. The study of the problems of Jet Engine Analysis was conducted in compliance with Contract AF33(616)-8508, Project No. 3147, Task No. 314702. This is the final report on the contract.

Included among those who cooperated in the development of engine testing methods and their evaluation were Mr. G. W. Weber and Mr. J. A. Elgin of the General Electric Large Jet Engine Department, Evendale. Consultation with respect to Computer operations was provided by Mr. R. W. Kettlety and Mr. C. W. Baldwin of the General Electric Computer Department, Phoenix. Acknowledgement is made of the assistance of Mr. W. J. Cake and Mr. E. G. Emery of the Pratt-Whitney Division of United Aircraft in providing the twin spool engine failure data and consultation on the tentative parameter limits established Acknowledgement is also made to Mr. Maxwell Dow of United Airlines for his help in data smoothing techniques.

The project was administered for the Aeronautical Systems Division, Directorate of Aerospace Ground Equipment Engineering, Checkout and Test Equipment Division, by Mr. Alva Pitsenbarger, who served as Air Force Project Engineer under the supervision of Mr. C. E. Lovett, Branch Chief and Sqn. Ldr. D. S. Eburne, Assistant Division Chief.

ABSTRACT

This report outlines methods of determining the condition of jet engines through measurement of performance sensitive parameters. The measurements required, test procedures, data processing, interpretation of results, and tentative limits are proposed. Estimates of the accuracy of the condition assessment, limiting conditions and measurement accuracies are included.

The "state-of-the-art" in engine condition determination through non-performance sensitive parameters is reviewed and programs for advancing it are proposed.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

Paul E Beck

PAUL E. BECK
Chief, Checkout and Test Eqp Div
~~Directorate of Aerospace Ground Eqp Engr~~
Deputy for Engineering

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List of Symbols

a - Temperature constant in hot section factor equation

$a_1, a_2, a_3 \cdots$ - Compressor discharge static pressure percent deterioration partials

A - Effective orifice cross section

A_1, A_2, A_3 - Turbine exit total pressure percent system sensitivity partials

A_4 - Turbine inlet cross-sectional area

ΔA_4 - Change in turbine inlet cross-sectional area

$b_1, b_2, b_3 \cdots$ - Fuel flow percent deterioration partials

B_1, B_2, B_3 - Fuel flow percent system sensitivity partials

$c_1, c_2, c_3 \cdots$ - Turbine exit total pressure percent deterioration partials

C $= k^2 \rho_0 / 2A^2$, orifice coefficient

C_1, C_2, C_3 - Compressor discharge static pressure percent system sensitivity partials

$d_1, d_2, d_3 \cdots$ - Turbine exit total temperature percent deterioration partials

$e_1, e_2, e_3 \cdots$ - Net thrust percent deterioration partials

f - Functional notation

$f_1, f_2, f_3 \cdots$ - Specific fuel consumption percent deterioration partials

F_1, F_2, etc. - Functional notation

F - Hot section factor

F_n - Net thrust

ΔF_n - Change in net thrust

$g_1, g_2, g_3 \cdots$ - Turbine inlet total temperature percent deterioration partials

k - Proportionality constant

k_c - Fuel flow correction coefficient for T_2 (P&W)

List of Symbols (Cont.)

K = $\sqrt{\frac{2A^2}{\rho_0}}$ orifice coefficient

L - Limit on deterioration parameter

m - Exponent applied to δ_2 to introduce Reynolds' number effect

n - Exponent applied to θ_2 in the corrected fuel flow expression (GE)

N - Rotor speed

N_1 - Rotor speed (low)

N_2 - Rotor speed (high)

N' = $N/\sqrt{\theta_2}$ corrected rotor speed

$\Delta N_1'$ - Corrected speed change or correction (P&W)

$\Delta N_2'$ - " " " " " "

P - Pressure

P_2 - Compressor inlet total pressure

P_{S3} - Compressor discharge static pressure (GE)

P_{S3}' = P_{S3}/δ_2^m , P_{S3}/δ_2 or P_{S3}/P_2 corrected compressor discharge static pressure as called for in the text

$\Delta P_{S3}'$ - Change in corrected compressor discharge static pressure

P_{S4} - Compressor discharge static pressure (P&W)

P_{S4}' = P_{S4}/P_2 , compressor discharge pressure ratio

$\Delta P_{S4}'$ - Compressor discharge pressure ratio change or correction (P&W)

P_5 - Turbine exit total pressure (GE)

P_5' = P_5/δ_2^m, P_5/δ_2 or P_5/P_2 corrected turbine exit total pressure (or engine pressure ratio, EPR) as called for in the text

$\Delta P_5'$ - Change in corrected turbine exit total pressure

P_7' = P_7/P_2 , engine pressure ratio, EPR (P&W)

List of Symbols (Cont.)

q	- Oil flow (volume)
sfc	- Specific fuel consumption
Δsfc	- Change in specific fuel consumption
t	- Time
T	- Temperature
T_2	- Compressor inlet total temperature
T_4	- Turbine inlet total temperature (GE)
ΔT_4	- Change in turbine inlet total temperature
T_5	- Turbine exit total temperature (GE)
T_5'	$= T_5/\theta_2$, corrected turbine exit total temperature
$\Delta T_5'$	- Change in corrected turbine exit total temperature
T_7	- Turbine exit total temperature (P&W)
T_7'	$= T_7/\theta_2$, corrected turbine exit total temperature
$\Delta T_7'$	- Corrected turbine exit total temperature change or correction
T_C, T_T, T_B	- Values of T_5' (predicted) taken from the 3-D plots of the compressor, turbine and burner (See Figures 3, 4 and 5)
V	$= \sigma^2$, variance
$V_{P'_{S3}}, V_{N'}$, etc.	- Variances of the P'_{S3}, N', etc., measurements
W	- Weight flow rate
W_a	- Compressor inlet airflow rate
W_b	- Bleed airflow rate
ΔW_a	- Change in compressor inlet airflow rate
ΔW_b	- Change in bleed airflow rate
W_f	- Fuel flow rate

List of Symbols (Cont.)

W_f'	= $W_f/\delta_2 \theta_2^n$ (GE) or $W_f/k_c \delta_2$ (P&W), corrected fuel flow rate as called for in the text
$\Delta W_f'$	= Corrected fuel flow change or correction as called for in the text.
x_n	- Value of the parameter determined at the nth test
$\bar{x}_n$	- Log average of n tests

Greek

α	- Percent difference in the predicted and measured values of T_5' corresponding to a measured P_5. (See Eq. 2.4-1 and Fig. 4);
α	- Also, log average smoothing factor as called for in the text.
$\alpha_1, \alpha_2, \alpha_3$	- Percent difference in the predicted and measured values of T_5' corresponding to a measured P_5' for the compressor, turbine and burner respectively (Refer Eqs. 2.4-49, 2.4-50 and 2.4-51)
β	- Percent difference in the predicted and measured values of T_5' corresponding to a measured W_f'. (See Eq. 2.4-2 and Fig. 5):
β	- Also, oil temperature coefficient of density as called for in the text.
$\beta_1, \beta_2, \beta_3$	- Percent difference in the predicted and measured values of T_5' coresponding to a measured W_f' for the compressor, turbine and burner respectively. (Refer Eqs. 2.4-52, 2.4-53, 2.4-54)
γ	- Percent difference in the predicted and measured values of T_5' corresponding to a measured P_{s3}'. (See Eq. 2.4-3 and Fig. 3)
$\gamma_1, \gamma_2, \gamma_3$	- Percent difference in the predicted and measured values of T_5' corresponding to a measured P_{s3}' for the compressor, turbine and burner respectively. (Refer Eqs. 2.4-55, 2.4-56, 2.4-57)
δ_2	= $P_2/14.7$, relative compressor inlet total pressure.
η_b	- Burner efficiency
$\Delta\eta_b$	- Change in burner efficiency
η_c	- Compressor efficiency
$\Delta\eta_c$	- Change in compressor efficiency

List of Symbols (Cont.)

Greek

η_t	- Turbine efficiency
$\Delta\eta_t$	- Change in turbine efficiency
θ_2	= $T_2/518.7$, relative compressor inlet total temperature
ρ	- Oil density
σ	- Error standard deviation in percent of point
ϕ_c	- Compressor efficiency function
$\Delta\phi_c$	- Change in the compressor efficiency function (Refer to Eq. 2.4-23)

Subscripts

a	- Air
b	- Bleed; burner as specified in the text
B	- Burner
c	- Compressor; corrected value as called for
f	- Fuel
m	- Measured value
n	- Net; last in a series of tests
o	- Initial or reference
p	- Predicted value
t	- Turbine
T	- Turbine
$Corr$	- Corrected
Ref	- Reference
HP	- High pressure
LP	- Low pressure

1.0 Introduction

1.1 Historical Note

The idea of jet engine condition determination through measurements made on the engine is not a new one. Practically all trouble shooting procedures are based on knowledge of performance during a malfunction, and prediction of troubles through systematic measurement of performance is a logical extension of this time honored method.

Some previous programs have examined various phases of engine analysis. To mention only two of several, WADC TN58-283 reports on a test on F86 airplanes in which only a few parameters were measured (oil consumption, coast down time, nozzle area, exhaust gas temperature, oil pressure) and was estimated as 35% effective in detecting troublesome conditions before excessive damage.

"An Engineering Study of Engine-Parameter Recording Techniques" in 1959 by Battelle Memorial Institute used a continuously recording automatic data acquisition system installed on a B-47 airplane. The conclusion of this work (started in 1956) was that a satisfactory recorder could be developed with some effort, although then currently available components were not completely satisfactory. The recorder system was found useful at the base level for determining immediate maintenance requirements and its use was suggested for long-term statistical studies of engine performance.

In 1960, the U.S. Air Force initiated a program to obtain evaluation samples of an airborne data acquisition system to be used for engine analysis. However, the program was modified and this study to determine the measurements and interpretations required for engine analysis was substituted.

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1.2 Purpose

The purpose of this study was to develop the theoretical aspects of the measurements and interpretive techniques required for the analysis of jet engines to

1. Determine the "health" of the engine
2. Isolate the source of any deteriorations
3. Predict engine life

with the ultimate aim of reducing maintenance cost and improving the reliability and readiness of the airplane fleet with an operationally practical system of engine analysis.

1.3 Conclusions

1.3.1 Measurement Areas

The study has revealed four measurement areas which have great potential in accomplishing the ultimate objectives of improving airplane reliability and readiness, and decreasing maintenance cost. These four areas are:

1. Thermodynamic performance sensitive parameter measurement
2. Vibration measurement
3. Time-temperature measurement
4. Lube system contamination measurement

Adequate data is not presently available to demonstrate quantitatively the magnitude of the improvement in airplane reliability and readiness or the reduction in maintenance costs available from measurements in any of the four areas listed. However, the spread in time to overhaul ranging from 100 to 1000 hours (6,29)* the airplane accidents and incidents caused by engines (7)*, the ten to one savings realized through early detection of bearing failures (8)* and the recently reported success in using vibration as an early warning of mechanical trouble (11)* indicate that very worthwhile gains are available.

1.3.2 Performance Sensitive Measurements

The thermodynamic performance sensitive measurements required for engine analysis are listed below. The computations and handling techniques required to interpret these measurements are described in detail in Appendix I.

* Numbers in parenthesis refer to bibliography

1.3 <u>Conclusions</u>

1.3.2 (Cont'd)

Compressor Inlet Total Pressure

Compressor Inlet Total Temperature

Compressor Bleed Air

Engine Speed

Engine Pressure Ratio

Compressor Static Pressure Ratio

Fuel Flow

Exhaust Gas Temperature

Lube Oil Pressure

Lube Oil Temperature

Lube Oil Consumption

Oil Sump Pressure

Oil Tank Pressure

Oil Flow (in press. reg. system)

Some method of "smoothing" the data must be used to reduce its normal variation to obtain meaningful results when compared to the limits. A geometric moving average as described in Para. 2.5.2, is one statistical technique that is satisfactory for this purpose.

In-flight measurements or gound based measurements, either automatically or manually recorded from current state-of-the-art equipment can be used insofar as accuracy considerations are concerned. Operational considerations, related to specific applications, can select the data acquisition system.

1.3.3 Vibration Measurement

Review of vibration data from jet engine users, vibration equipment manufacturers, and Air Force studies has indicated three kinds of vibration measurement. These are (1) broad band, (2) vibration signature, and (3) tachometer ratio methods. Each of the methods have some advantages either in simplicity or vibrating component isolation capability. Summarizing, it is evident that vibration measurement is a powerful tool in determining the mechanical integrity of the engine and that further evaluation of the tool is required for application in a jet engine analyzer. Recommendations for the next step in this program are included in Sec. 3.

1.3.4 Time Temperature Measurement

Time-temperature measurements were reviewed with engine manufacturers, engine users, and through metallurgical texts and reports. Several modes of failure such as stress rupture, creep, and thermal fatigue cracking are prevalent in some hot section engine components. On some engines where the failure is through creep or stress rupture and stress and temperature are functionally related, the time integral of the proper function of temperature can provide a good index of hot section life. On engines where the failure is through thermal fatigue cracking, the time integral of temperature is not related to component life. In engines where the stress and temperature are not functionally related, a time integral of the proper function of stress and temperature is necessary to obtain an index of hot section parts life. In general, the time-temperature measurement requires considerably more development. Recommendations for further work on this parameter are included in the report.

1.3.5 Lubrication System Contamination

Lubrication system contamination measurements have few reports applicable to jet engines, although some engine users rely on it for initiation of maintenance action. Successful use of the measurement depends upon obtaining a representative sample of the contaminating material. This, in turn, depends upon filter or plug location and lube system design. As in the case of vibration and time-temperature, further evaluation and technique development are required to realize the trouble detecting capability of this measurement. A practical procedure to evaluate this measurement is included in the recommendations for continued effort in the field of engine analysis.

1.4 Recommendations

An evaluation program to determine the magnitude of the gains that can be made in airplane reliability, readiness, and maintenance cost reduction is required before large scale implementation of an engine analyzer program is undertaken. This data is not currently available because there have been no programs, recording regularly engine performance measurements for correlation with malfunction history or inspection findings.

This program can be pursued with minimal hardware as outlined in Sec. 2.8 and 3. Basically an airborne data acquisition system recording continuously during flight (i.e. measurements about once every five seconds) will give the most complete evaluations. With proper procedures, such a system will provide a comparison of ground based or airborne, manual or automatic data acquisition. The evaluation program should not attempt to prescribe maintenance action on the test vehicle but it should establish in retrospect, those malfunctions and deteriorations which correlate with the measurements. On this basis, extensive computer facilities to meet exacting time schedules are not required.

The road to a final configuration of an operationally suitable engine analysis technique is a step by step application and integration of the methods of engine condition assessment outlined in this report. The next step along the road should be the evaluation program, discussed above and in Sec. 3, to correlate observed engine deteriorations and malfunctions with regularly recorded engine measurements.

2.0 Discussion

2.1 General

This report covers the results of a study to develop a method of analyzing a jet engine to detect incipient engine failure or engine deterioration before excessive secondary damage is done. The kinds of failures occurring, the measurements required for their detection, and the methods of treating the measurements to obtain a maximum of information from them are all explained in detail in subsequent sections.

The procedures and methods of using the performance sensitive parameters for engine condition assessment were developed by the engine manufacturers. Tentative limits on allowable parameter variations were established through the use of a computer model of the engine to simulate the performance of new and degraded engines, and by manufacturer and user experience where this was available. Estimates of the proposed analyzer system accuracies were made by combining the results of sensor, transducer, recorder and computer studies to provide statistical estimates of the overall systems accuracies.

The state of the art in using the non-performance sensitive parameter for engine condition assessment was examined through data from engine manufacturers, equipment manufacturers, engine users, and related Air Force programs. The study of this data provides the basis for the description of the programs to evaluate and develop further the use of these parameters for engine analysis.

2.2 Failure Data

This section tabulates some of the historical records of engine failures, overhaul actions, and engine inspired incidents. Search of Air Force, and engine manufacturer records has not revealed adequate data where a correlation of regularly acquired measurements with observed failures or malfunctions can be made. Air Force records showing engine inspired accidents or incidents correlated with the engine culprit component are readily available, as are records from the overhaul depots detailing overhaul actions. Engine manufacturers were very helpful in providing records from their reliability and product improvement programs showing the premature overhaul actions, in-flight power loss events, malfunction detection means etc. None of these data include a historical record of engine measurements against which the observed events or overhaul findings can be correlated to determine which measurements are effective in providing early detection and isolation of the malfunction.

Commercial airlines were very cooperative in discussing their engine analysis programs which in general are just starting to accumulate historical data for early malfunction detection. The results of these programs are encouraging with respect to demonstrating an ability to detect some engine discrepancies before catastrophic failure, although it is too early to estimate the effectiveness of the measurements, and application of airline experience to military engine operation is questionable. (See Par. 2.2.4.)

2.2.1 Air Force Accident/Incident Record

The data summarized in this section were taken from studies NR10-59 and NR6-61 of the Engineering Branch -- Directorate of Flight Safety Re-

search -- Norton AFB, California. The original reports are titled "Turbojet Engine Failures and Malfunctions Involved in USAF Accidents/Incidents."

The reports indicate the following areas of the engine were responsible for the given percentage of accidents/incidents during a 3-year period from July 1957 to July 1960.

TABLE I

USAF ACCIDENTS/INCIDENTS 1957-1960

Area of Malfunction	% Total Accident/Incident
Fuel System	31.3
Compressor	14.5
Main Brg & Lube	10.3
Turbine	11.7
Accessories	5.4
Combust. & Exh.	4.5
Undetermined	15.7
Personal Acts.	6.6

Examining data presented on fuel system malfunctions in more detail, it is found that:

1/3 of total is due to Fuel Icing

1/3 of total is due to Fuel Control

1/6 of total is due to All other Fuel System Components

1/6 of total is undertermined

Of the 1/3 of the total accidents/incidents due to fuel icing, 80% of them occurred on one engine-airplane combination (J33-T33); the balance on fifteen other engine-airplane combinations.

Of the total compressor problems, 1/4 occurred on one engine-airplane combination (J35-F89); the balance on fifteen other engine-airplane combi-

nations.

Of the total bearing and lubrication system problems, 1/4 is associated with one engine-airplane combination (J57-B52); the balance on 12 other combinations.

In general, in each area listed in Table I, one engine-airplane combination was responsible for about twice as many of a particular malfunction as the next highest combination. Although relative flight hours on the various airplanes is not given in the study for security reasons, the fact that different engine-airplane combinations are responsible for a majority of each kind of malfunction shows that exposure is probably not responsible for the phenomena, and that for given time periods, particular ills beset different aircraft.

2.2.2 Single Spool Engine Failure Data

The single spool engine failure data was accumulated largely through the General Electric Company's program of reliability evaluation. The study is a continuing one; the data taken from it for this report covers the period from Dec. 1958 to Oct. 1961. The data from this program shows a very significant ratio of power loss events caused by the controls and accessories as compared to the main engine.

TABLE 2

POWER LOSS EVENT RATIO

Malfunction Source	Percent of Power Loss Events
Main Engine	16-20
Control & Accessory	84-80

For the purposes of the reliability study, a power loss event is defined as a 10% loss in thrust from the operating power level.

Breaking down the Control and Accessory total events requiring maintenance action, including those which caused power loss as well as those which did not, it is seen that one component, the temperature amplifier, caused twice as many maintenance events as any other single item, and that six components caused over half of all the maintenance actions taken.

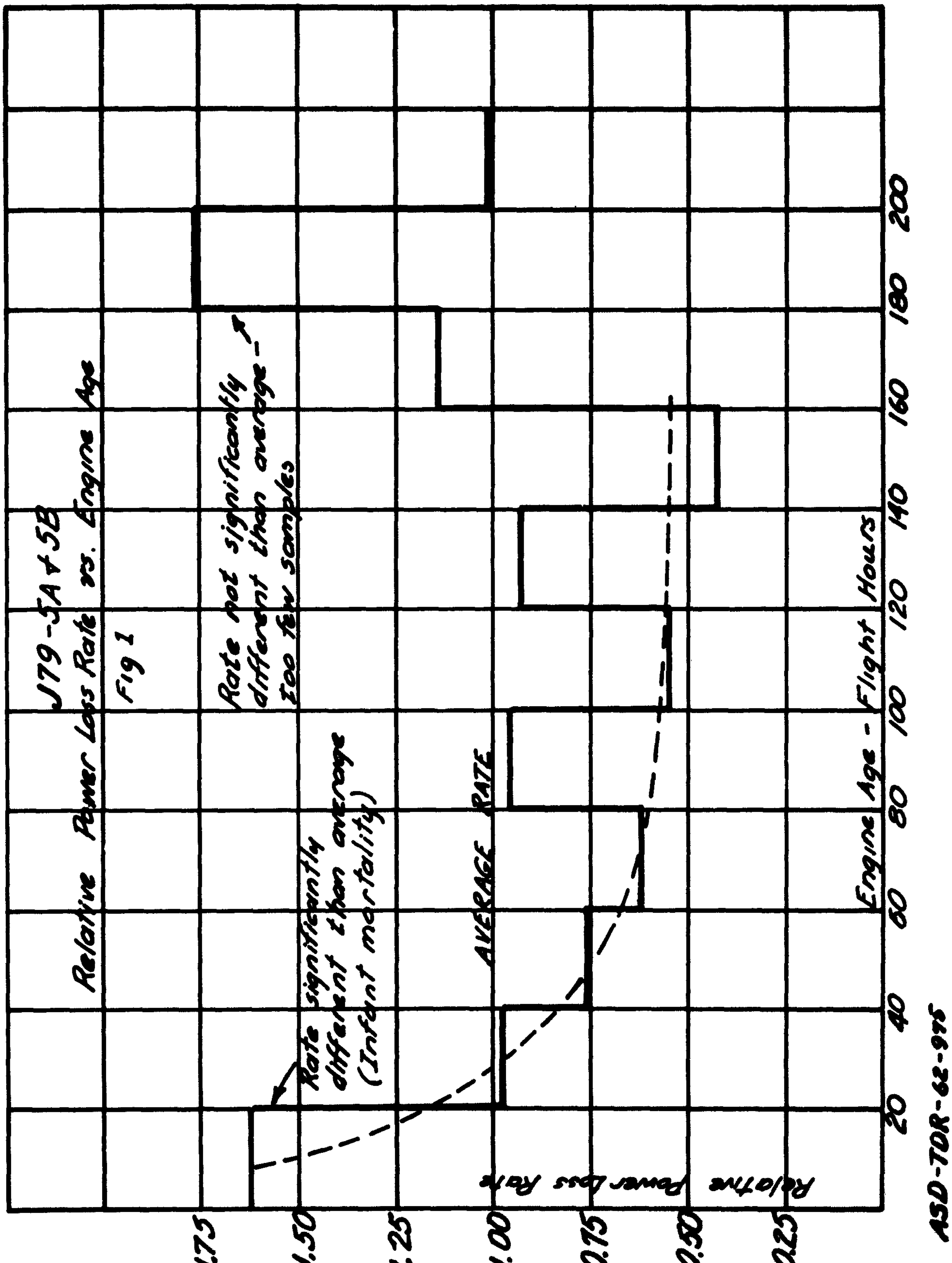
TABLE 3

CONTROL & ACCESSORY TOTAL EVENTS

Component Causing an Event	% Total Events	Cumulative % of Total
1. Temperature Amplifier	18.3	18.3
2. Anti-Icing Valve	9.1	27.4
3. Main Fuel Control	8.8	36.2
4. Pilot Burner Orifice	5.9	42.1
5. Noz. Area Cont. Servo Filter	5.3	47.4
6. Prim. Noz. Area Control	4.5	51.9
7. Prim. Noz. Area Sensor	4.2	56.1
8. A/B Spark Plug	4.0	60.1
9. Control Alternator	2.8	62.9
10. Sec. Noz. Pump	2.7	65.6
11. Press. & Drain Valve	2.4	68.0
12. Main Lube & Scav. Pump	2.2	70.2
13. Comp. Inlet Temp. Sensor	2.1	72.3
14. Variable Stator Feedback	2.1	74.1
15. Flow Div. & Sel. Valve	2.0	76.4
16. Prim. Noz. Feedback	1.8	78.2
17. Fuel Seg. Valve	1.8	80.0
18. Pilot Burner Filter	1.7	81.7
19. A/B Fuel Control	1.5	83.2
20. Press. Noz. Pump	1.5	84.7
21. Anti-Icing Switch	1.3	86.0
22. Pilot Burner	1.0	87.0
28 Misc. Components	13.0	100.0

This performance is quite typical of new engine-airplane combinations, and is a condition that does not exist for long periods of time, because product improvement programs concentrating on the troublesome items usually solve component problems of this kind very quickly.

The results of investigating engine failure rates (i.e., power loss events), vs. engine age are shown on Fig. 1. This curve illustrates that as far as the data goes, which is only to two hundred hours flight time, that wear-out phenomena are not causing the engine failures that are occurring, but rather they are caused by random operating excesses or material inconsistencies.


Relative Power Loss Rate vs. Engine Age
J79-5A + 5B
Fig 1
Rate not significantly different than average - Too few samples
Rate significantly different than average (Infant mortality)
AVERAGE RATE
Engine Age - Flight Hours
Relative Power Loss Rate
1.75
1.50
1.25
1.00
0.75
0.50
0.25
20
40
60
80
100
120
140
160
180
200
ASD-TDR-62-995

2.2.3 Twin Spool Engine Failure Data

Data on the twin spool engines was supplied by Pratt & Whitney Aircraft. Following are several excerpts from the transmittal letter accompanying the data.

"It can be seen from these listings (malfunction detection means - Table 6) that the simple act of looking at the engine with a knowing and critical glance turns up many, if not a majority of the malfunction evidences. We feel that power plant inspections will remain high on the list of necessary preventive actions for many years to come."

"It should be particularly interesting to note how the pattern of malfunctions change from year to year, -- These factors of the changing pattern of malfunctions are one reason why an engine monitoring system should be capable of sensing the maximum number of engine parameters in order that it be useful over the entire life of the engine."

A summary of the data (Table 4) shows that the highest ten failure items in 1958 were not the most important in succeeding years.

TABLE 4

MALFUNCTION CHANGE VS. TIME

Year	Percent of Malfunctions Covered by 10 Most Important Items in 1958
1958	80
1959	75
1960	30

In succeeding years (Table 5) the ten highest failure items in each year cover a smaller percentage of the total trouble.

TABLE 5

MALFUNCTION CHANGE VS. TIME

Year	Percent of Malfunctions Covered by 10 Most Important Items in Year Listed
1958	80
1959	78
1960	50

This points out that, with experience, major problems are recognized, remedies found, and reduction of trouble from the big items increases the number of items needed to detect any given percent of total malfunctions.

The most important means of detecting malfunctions are summarized on Table 6 below.

TABLE 6

MALFUNCTION DETECTION MEANS

Detection Means	Percent of Malfunctions*		
	1958	1959	1960
External Visual Insp.	39	11	18
Oil Loss **	27	62	22
High EGT	10	3	3
Internal Visual Insp.	9	4	6
Gas Generator Curves	2	2	3
Vibration ***	2	7	5
High Breather Press.	0	3	0

* Percentages do not add up to total of Table 4 & 5 because many malfunctions are detected by more than one means.
** Includes oil overboard, oil consumption and oil leaks.
***Many of engines covered by report not equipped with vibration monitoring equipment.

Tables 4, 5, and 6 verify the statements quoted from Pratt & Whitney's transmittal letter. Data from General Electric was not broken down vs. time, hence documentation of supporting evidence is not available. However, the

implications of the shifting pattern of malfunctions with time were verified by oral discussions with GE Engine Depts.

Both engine manufacturers gave data showing the reason for overhaul on their respective engines. Differences in presentation and interpretation can be expected to cause some differences in the numbers shown for the various items, and corresponding summaries covering different time periods would undoubtedly show a somewhat different distribution of the reasons for overhaul. However, the data shown in Table 7 correlate very well so that a common system of engine analysis is not precluded by drastically different problem areas. The major difference in the figures occurs in the removals for vibration, and it was previously pointed out (Table 6) that vibration measurement was not used to prescribe overhaul action for the twin spool engines. Review of single spool engine data for a later period shows a much lower vibration incidence and indicates that this was one of the problems peculiar to a particular time period that has been corrected by remedial action.

TABLE 7

OVERHAUL DATA SUMMARY

Reason for Removal	Percent of O/H Actions	
	GE Data	P&W Data
Vibration	29.2	2.2
High EGT	4.8	2.9
Low Perform.	0.5	0.7
Unknown	12.4	4.8
Oil System	22.2	22.8
Seals	13.6	19.6
Compressor	4.9	7.6
Bearings	3.7	2.8
Turbine	1.6	5.2
Hardware	0.9	8.3
IGV	0.9	---
Combust. Chamb.	0.6	0.4
Fuel Systems	0.4	2.1

2.2.4 <u>Commercial Airlines</u>

Statistical data on engine failures was not obtained from the commercial airlines because the non-afterburning engines they use, their use of the engines, and their overhaul policies are so different from the Air Force that data of this kind could not be considered comparable. However, a survey of airline practices in malfunction detection was made and their experience is worthy of note.

Practically all of the airlines have had some experience with vibration measurements with varying degrees of success. The vibration measurements are usually made with pickups at either the diffuser case or turbine frame or both. The pickup signals are filtered selectively through "high pass" filters to remove low frequency air frame vibrations. Two filters are used on twin spool engines to provide some separation of "hi" and "lo" rotor frequencies. Measurements are generally made quite frequently during the cruise portion of the flight (read every 15 minutes, recorded every 30 minutes, on one airline). The in-flight vibration measurement is used to prescribe engine shut down under some circumstances.

Reports of the effectiveness of the vibration measurement in providing early warning of engine malfunction and damage limitation range from a figure of 80-90 percent of confirmed vibration incidents (Am Airlines - P&W Report FLOE-25) to reports of so many false indications that the measurement has been discontinued at least for a time. One airline has reported vibration variations of 40% on a single flight in steady state cruise on a "good" engine and has also noted correlation of vibration with altitude and fuel flow on some engines. Most airlines are working with vibration to develop the techniques of measurement and interpretation.

None of the airlines are currently using a time-temperature index for hot section parts life although most of them have investigated this parameter and were impressed with its potential. The reasons for not using it are the uncertainty of the function for integration, the uncertainty of the limits, and the legal specification of allowable time between overhauls.

Measurement of performance sensitive parameters for the detection and prediction of jet engine malfunctions is relatively new in the airlines, and little data correlating malfunctions with measurements is available. However, most of the airlines have data collection and analysis systems of various degrees of sophistication.

Data collection about once or twice a flight by the flight engineer is considered adequate. Some airlines correct the observed data for ambient pressure and ram air temperature, others compare the performance of each engine to the average of the four engines on the airplane to detect changes in one engine from the average of the four. In most cases there is some data reduction and computing done in flight by the flight engineer, and in some cases the complete data reduction and plotting with a data smoothing technique is done in flight so that on landing, a complete history of the last 30 to 50 flights is immediately available.

Ground based automatic data logging at a central location is used to maintain a complete history of each engine. This history is from four to ten flights behind the airplane. It is available to maintenance crews through telephone or telegraph at any time it is wanted, and is also used for long time statistical studies of fleet performance. Analysis of some performance data has shown that over long periods of time encompassing many overhauls there is a small increase in exhaust gas temperature and a small

increase in specific fuel consumption. So far these are the only manifestations of "wear out" phenomena, but no engines have been declared unsatisfactory for use on the basis of these minor deteriorations in performance. A report from Trans Canada Airlines, "Overhaul Life Development and Early Failure Detection of Gas Turbine Engines" by J. J. Eden in June 1962 makes the statement that engine failures experienced by TCA cannot be correlated with total engine time nor time since overhaul.

Most airlines were very cautious in their statements regarding engine condition determination through measurement of performance sensitive parameters because the controlled programs in this area are just getting started. However, instances of detecting damaged burner cans, damaged turbines, and fouled compressors were quoted. The fact that the airlines are initiating these programs at considerable expense indicates they believe there are worthwhile economies and safety improvements to be obtained from analysis of these records.

2.2.5 Failure Data Discussion

Engine failures can be classified by the nature of their occurrence as:

1. Very slow deterioration
2. Relatively rapid deterioration or sudden change - not catastrophic
3. Sudden catastrophic failure

The first class of deteriorations is typical of gradual erosion from external sources. The second class of deteriorations is typified by bearing or burner deterioration that create a condition which causes a progressively increasing deterioration rate, while the third class is exemplified by catastrophic foreign object damage.

The sudden catastrophic failure that gives no warning of its imminence (such as foreign object damage) has been recognized from the beginning as a kind of failure whose prediction is impossible.

The relatively rapid deterioration or sudden change that is not immediately catastrophic is the kind of event that can be detected through chronological records of pertinent measurements. Early detection of these events is very important in reducing possible secondary damage caused by a relatively insignificant failure. Much of the study effort has been directed at the selection and treatment of parameters which should be monitored to detect these events that are reflected in the thermodynamic performance of the engine.

The very slow deterioration that is sometimes considered normal wear out is detected by the same measurement as the rapid deteriorations only it occurs much more gradually. Although present evidence does not indicate that jet engine failures are occurring from this cause, chronological records of performance sensitive and non-performance sensitive parameters are the only means known for detecting this kind of change and providing an estimate of the rate of deterioration.

Since consideration has been given to the use of the engine analyzer to extend overhaul periods, it should be pointed out that operating a system in the period of time when component wearout is effective in causing failures, provides an extremely unreliable system performance and is a condition of operation that should be avoided. The ability of the engine analyzer to detect either the gradual wear out or rapidly occurring non-catastrophic event should be used to insure that engines are not being used into the period when wear out failures are significant.

Examining the data relating to the Class 2 failures, the single spool engine data indicates that many more failures (a failure is classified as a 10% thrust loss from the operating power level) are due to the controls and accessories (Table 2) than are due to the main engine. (Although figures were not available for twin spool engines for comparison, the general ratio was corroborated in oral discussion with P&W.) This is an area of the engine where measurements of condition are not generally advisable (See Par. 2.6.1), thus knowledge of these control and accessory inspired events is in general not available.

Under these conditions as reviewed with respect to the control and accessory area, and recognizing the random nature of the majority of engine incidents, total life prediction on a specific engine cannot be considered highly accurate. Subsequent sections of this report describe the measurements and procedures that will provide early detection of those faults which give warning prior to their occurrence.

2.3 Non-Performance Sensitive Measurements

Two general degradations can take place in an engine, (1) those which result in impairment of the mechanical integrity of the engine but are not reflected in its thermodynamic performance, and (2) those which result in a change in the thermodynamic cycle of the engine. A complete engine analyzer system should be capable of detecting both kinds of deterioration and providing interpretable data about them.

This section discusses the first category of deteriorations which are called non-performance sensitive, and do not affect the thermodynamic cycle of the engine. Three such measurements are considered worthy of evaluation and development in a continuing program for engine analysis, they are (1) Vibration (2) Time-Temperature (3) Lubrication Contamination.

2.3.1 Vibration

Vibration analysis of jet engines is currently being studied carefully by practically all segments of the industry concerned with jet engine operation, maintenance, and manufacture. It is regarded generally as a very valuable index of the mechanical condition of the engine. The accuracy and extent to which vibration data can isolate the location and magnitude of specific faults has not been completely demonstrated.

In other industries, notably electric motor manufacture, air conditioning equipment manufacture, and some segments of the automotive industry vibration measuring techniques have been developed for production inspection operations with a high degree of success - a success due in large part to the ability of the technique to isolate

the faulty components of complex assemblies quickly and accurately. The evidence accumulated indicates that this same success may be achieved by vibration analysis of jet engines. However, the techniques for using vibration of jet engines have not been developed sufficiently to permit the specification, with assurance, of either equipment or procedures that will provide data that can be interpreted satisfactorily.

Most vibration equipment in use today senses the total vibration in a single direction with one or two pickup locations on the engine. (See par. 2.2.4) The data has been used in a precautionary way (i.e., remove from service engines showing out of limit performance) rather than diagnostically (locating the source of trouble directly from vibration measurement). Varied degrees of success are reported for this kind of vibration measurement (See par. 2.2.4) and continued effort is being expended on developing techniques of measurement and interpretation.

More elaborate equipment is available which utilizes means of examining vibration frequencies of specific ratios to some engine characteristic frequency (usually rotor speed). With this equipment it is possible to examine the rotating frequencies of engine accessories, pumps, generators, etc. in more detail and isolated from the main rotor vibration which usually is larger. As yet, verification of the ability to isolate faults to a specific component or engine area, on a statistically significant number of cases, has not been found.

A very extensive program to develop this approach to vibration measurement through mathematical analysis of the engine correlated with measurements is underway on Air Force Contracts AF 34(601)-4412 and AF 34(601)-9593 at the University of Oklahoma. This work has pro-

gressed through the establishment of a procedure for pinpointing many mechanical faults to experimental verification of the theoretical analysis. Results of the verification program are not available at this writing.

The procedures tentatively contemplated through this study can be performed relatively simply in a test stand, however, in-flight performance of the procedures would be quite impractical, and even flight line performance of them would be an arduous and time consuming operation. This proposed analysis method has a great deal more significance as a detailed diagnostic tool after simpler procedures have determined the requirement for this detail.

The most complex equipment has the capability of examining a range of frequencies up to 20 Kc/sec through a very narrow band pass filter, picking out specific frequencies for examination. This is the most general approach, and potentially the most powerful. Most experience with this equipment is with industrial rather than jet engine applications but there is considerable similarity in the problems.

The application of this method to the inspection of automotive differentials, air conditioning units, electric motors and watches is reported in the Bruel & Kjear Technical Review of April 1957. In this review it is pointed out that not only is a go-no go inspection performed but that the test record provides a diagnosis of the ailing component of the assembly.

Case histories of several airplane vibration problems solved by use of essentially the "signature" method are reported in a paper "Elimination of Vibration as a Destructive and Costly Element in Air Force Materiel" by Walter M. Bass, AMC, Wright Patterson AFB.

From the vibration measuring equipment available, the success in industrial use of this parameter, and the conflicting evidence from the jet engine field on the use of broad band vibration measurements, it is apparent that an evaluation program for vibration analysis of jet engines is in order. This program should examine carefully and determine the area of application of each of the three fundamental methods of vibration which can be described as

a) A gross vibration measurement in which a vibration index encompassing a broad frequency band is measured (broad band vibration method)

b) A scan of a vibration index vs. engine speed in which certain frequency ratios to main rotor frequency are monitored. (tach. ratio method)

c) A panoramic scan of vibration index vs. frequency at constant engine speed and with a narrow band pass filter. (vibration signature method)

Among the items comprising the techniques that require development are

1. The bandwidth and attenuation characteristics of the filters
2. The scan rates
3. The number and location of the sensors
4. The best units of vibration measurement (i.e., amplitude, velocity, acceleration)
5. The best engine speed or speeds

6. The frequency range

A program for evaluation of vibration measurement is proposed in Section 3.

2.3.2 Time-Temperature

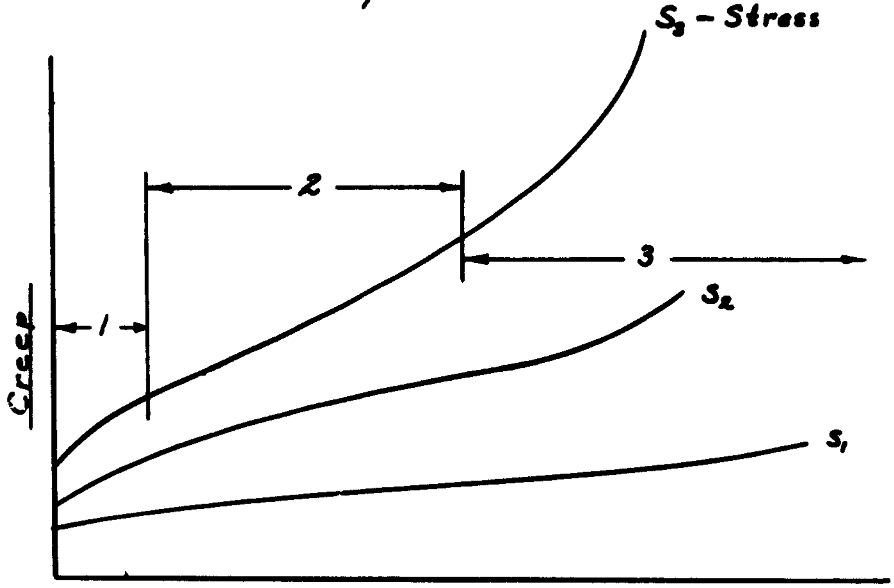
One of the critical deterioration areas of a jet engine is in the "hot" section containing the combustors, turbine nozzle guide vanes, and turbine. In this region aging or deterioration is of primary importance because failure of these components can cause extensive secondary damage to the engine and in some cases to the airframe. In spite of the advanced state of the art in jet engine manufacture there is no sure method for measuring the "age" of jet engine hot sections in service.

There are at least two modes of deterioration of hot section components. One is through growth or creep of the parts under stress and temperature, and the other is cracking due to internal stresses generated by temperature gradients.

Growth or creep of materials under stress and temperature has been studied for many years, yet a completely satisfactory theory explaining it or mathematical description of it has not been devised. General studies of the subject show that the creep or growth is a non-linear function of time, temperature, and stress. The curves of Fig. 2 show the general form of this function at one temperature and three stress levels.

Fig. 2

Creep vs Time



Time-Temperature-Stress Characteristic

Three general kinds of creep are evidenced in these curves; initial deformation at relatively high strain rates (1); the period of constant or minimum strain rate for the applied stress (2); and the final deformation prior to rupture at an increasing strain rate caused by "necking down" of the cross-sectional area due to deformation (3). For higher temperatures the general shape of the curves is about the same but the slope (i.e., creep rate is greater).

Empirical correlation of data on the materials and application in some jet engines has led to the definition of a "hot section factor," F. This hot section factor is the ratio of the rate of creep of the hot section components at some temperature T to the rate of creep at temperature T_1 which is a reference temperature below which the rate of creep is considered constant and very small. It has been proposed that integrating the

factor "F" vs. time will provide a measure of the "equivalent" hours of engine operation which is the "age" of the engine.

$$\text{Engine Age} = \int_0^t F\,dt$$

On some engines, there is evidence that the hot section factor "F" can be described by an equation of the form

$$F = e^{a(T-T_1)}$$

where the temperature T is the exhaust gas temperature measured down stream from the turbine.

This form of the hot section factor, as a function of temperature only, applies generally only to fixed geometry engines. Variable geometry engines in which the exhaust gas temperature is controlled by varying the exit nozzle area require a bias of the E.G.T. as a function of some measurement up-stream of the hot section. At this writing the form of the equation describing the hot section factor for variable exit geometry engines has not been crystallized.

Since the temperature being measured is not the actual temperature of the components, evaluation of the constants and establishment of the limits must be done on each engine model, and it may be that different components in the engine such as burner cans, nozzle guide vanes, turbine buckets, etc., will have different factors to integrate. Extensive testing on engines is required to establish these facts with certainty. Some initial work along these lines has been started at Andrews AFB using the F106 airplane as a test vehicle. The objective of the program is to obtain correlation of hot section deterioration with an estimated hot section factor.

Results from the program are unavailable at this writing.

The above discussion refers only to the creep or growth of engine hot section components under stress and temperature. The second mode of failure, cracking due to internal stresses generated as a function of temperature gradients, follows quite different laws. With engines that are failing in this mode, the number and severity of temperature transients are more important than time at any particular temperature. Correlation of engine condition with number of starts, or number of complete cycles has been used in some cases. A great deal more study of this mode of failure is required before it will be possible to describe with assurance a measurement other than physical inspection that will accurately portray this deterioration on those engines where it is significant.

Section 3.0 describes an evaluation procedure that can be easily integrated with the evaluation tests of the performance sensitive parameters and will help in establishing the hot section factor relation to life if the test vehicle selected has hot section life limited by creep or growth.

2.3.3 Oil Contamination Analysis

Measurement of the level of the metallic contaminants in the lubricating oil has been proposed as a method of detecting mechanical distress of the oil wetted parts of the engine. This method has been used by railroads for some time in determining the condition of diesel equipment. In 1955, the Fleet Readiness Group of the Bureau of Naval Weapons initiated a project at Pensacola to determine if this concept were applicable to aircraft piston engines. The conclusions were favorable, (AD268305) and early in 1961 the Navy was monitoring 2200 engines and helicopter transmissions by spectro-

graphic oil analysis. Complete statistical data has not been requested from this operation but over a period of several months on 483 engines being monitored 34 actions were taken of which 33 were verified by the findings and one was not.

More recently and more appropriate to jet engines, Trans Canada Airlines has examined contamination analysis of lubricating oil on their jet engines and report quite favorably on it. ("Overhaul Life Development and Early Failure Detection of Gas Turbine Engines" by J. J. Eden, June 1962). No engines have been removed so far on the basis of the spectrographic analysis as the "objective of the program has been to establish in retrospect whether correlation between failure and metal content was consistent." "In the case of the Conway engine very good correlation between iron content and bearing failure has been obtained. Iron has been the only element giving correlation to date. This has been obtained in a positive form which would permit the setting of contamination levels of Normal, Suspect, and Danger." "A similar program is underway on the Tyne engine -- results are not as clear as for the Conway engine -- further experience is necessary before deciding whether correlation exists." The TCA report further indicates that bearing distress detected early required an average of $4000 worth of material to repair, whereas bearing failures in-flight required an average of $50,000 worth of material to repair.

Examining the concept of oil contamination analysis indicates many problems. The main parts of the engine which shed particles into the oil system are bearings, gears, seals, and splines. The particles that appear in the oil system occur in a wide range of sizes. The smallest remain in suspension indefinitely in the oil - these little particles come from fretting types of wear such as bearing race spinning or spline wear. The larger particles will

generally not stay in suspension and tend to get caught in corners of the scavenge system - these larger particles come mostly from fatigue failures in balls, rollers and races of anti-friction bearings and gear tooth spalling.

The small particles suspended in the oil can be detected best by quantitative spectrographic analysis of the oil. The larger particles are very apt to be missed in the spectrographic sample and are best detected by strategically located magnetic plugs or examination of the oil filter contents. The advantage of these methods is that they seem to provide an early enough warning so that action can be taken before extensive damage has been done to the engine. The disadvantage is that the methods require considerable attention from well-trained, conscientious personnel.

The problems of oil contamination analysis then can be summarized in two general classifications.

1. Contamination detection means and interpretation of contamination level

2. The sample handling and data communication problem

Indications from the TCA tests are sufficiently encouraging to suggest that an evaluation on USAF airplanes be made to investigate at first hand the correlation, and communications problems involved.

2.4 Engine Analysis with Performance Sensitive Parameters

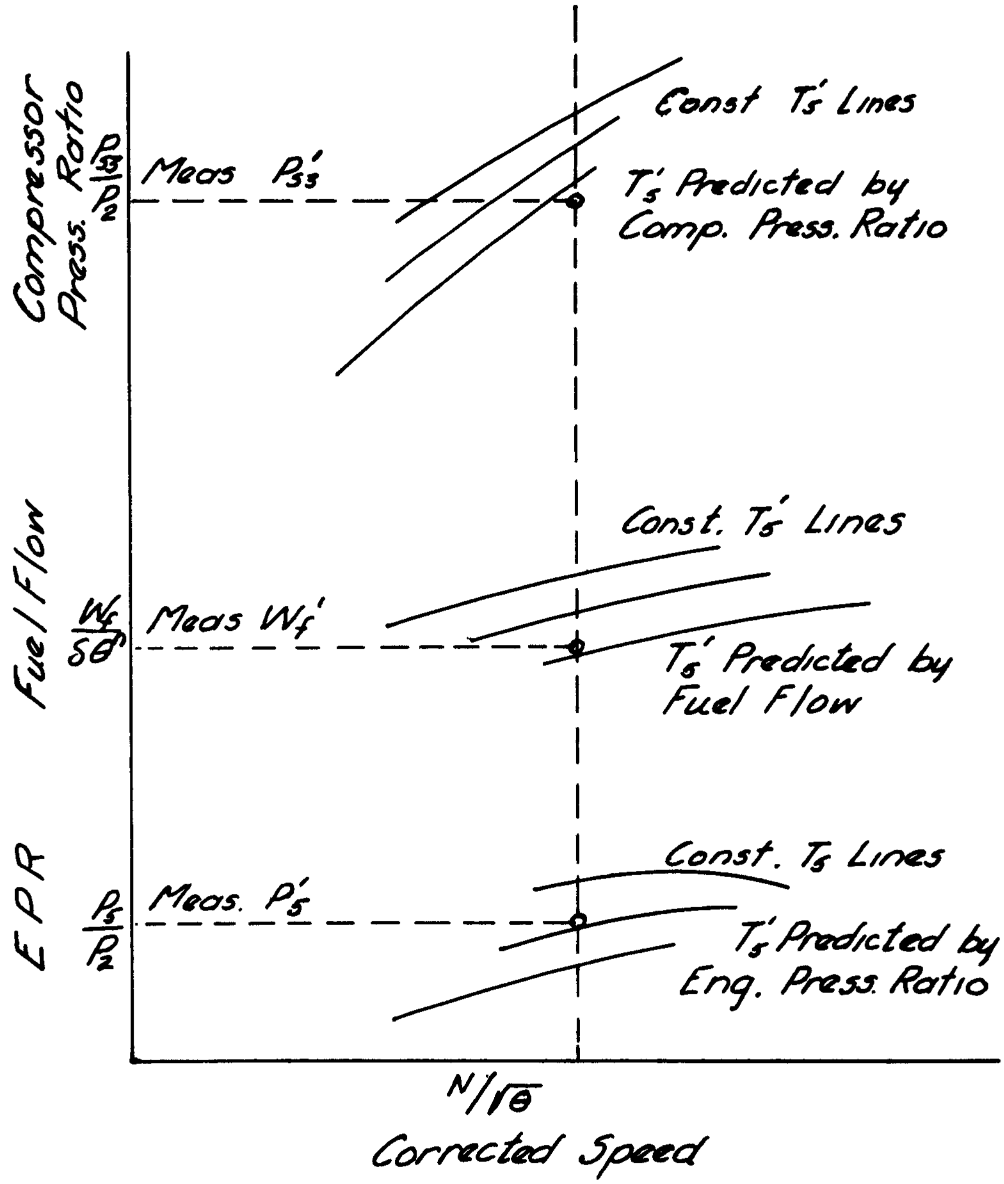
This section summarizes the methods developed to determine the deterioration or performance changes of single and twin spool jet engines from the measurement of thermodynamic performance sensitive parameters. A detailed description and development of the methods is covered in Appendix I.

2.4.1 Single Spool Engine Performance Analysis

The single spool engine analysis method uses a comparison of predicted and measured exhaust gas temperature to indicate a change in the engine performance. Using these EGT comparisons through a system of quantitative logic, engine deterioration can be isolated to the major functional components of the engine (i.e., the compressor, combustor, or turbine) and simultaneously occurring deteriorations can be separated.

In the analysis procedure, a "predicted" exhaust gas temperature is determined from curves based on the performance of an ideal engine. These curves are illustrated in Fig. 3 below. From simultaneous observations of the engine speed, pressure ratio, fuel flow, and compressor static pressure ratio, three values of corrected EGT are predicted. The difference between these predicted EGT's and the measured EGT is an index of deviation of a specific engine from the average or generic engine.

Fig. 3
Single Spool Engine
Generic Performance Curves



This difference unless it is large is generally not significant since manufacturing variations in components and adjustments cause engine differences. Changes in this difference of predicted and measured EGT during the life of an engine are indicative of changes in the thermodynamic performance of the engine, and are used as a measure of engine deterioration.

From a computerized mathematical model of the engine it has been possible to relate the magnitude of the change in predicted and measured EGT to the magnitude of changes in the performance of the functional components of the engine. These relations can be arranged in tabular, or matrix form as illustrated in Table 8 below.

TABLE 8

SINGLE SPOOL ENGINE

PERCENT SYSTEM SENSITIVITY PARTIALS

Component Deterioration Function	% Difference between predicted and measured EGT		
	Obtained from P_s', N' Curves (α)	Obtained from W_f', N' Curves (β)	Obtained from B_s', N' Curves (γ)
Compressor $\% \Delta \phi_c$	A_1	B_1	C_1
Turbine $\% \Delta \eta_t$	A_2	B_2	C_2
Burner $\% \Delta \eta_b$	A_3	B_3	C_3

In this table, the capital letters designate the magnitude of the change in the difference between predicted and measured EGT for a one percent change in the component deterioration function. Knowledge of

the numerical values of the capital letters is derived from the "computerized" engine, so the matrix can be solved for the deterioration of the components when measurements of the pressures, fuel flow, engine speed and temperature are known.

Plotting the changes in component deterioration vs time shows any gradual deterioration or sudden change. Extrapolation of the trend of these measurements until they reach a limit provides the estimate of total life remaining in the engine.

Establishing the allowable limits on the component deteriorations was done by examining the effect of component deterioration on significant performance characteristics through the computer simulation of the engine. The criteria used for establishing the limits are whichever of the following occurs first:

1. 10% loss in thrust
2. 10% increase in specific fuel consumption
3. 4 times increase in consumption of hot section parts life
4. Any mechanical or operational difficulty produced by the deterioration.

On this basis, the compressor deterioration function is limited to a change of 2% because this causes too large a reduction in stall margin; the turbine and burner efficiencies are limited to 5 and 10% changes respectively because this causes a 10% increase in specific fuel consumption. These quantitative determinations are based on J79 engine performance. The same principles apply to any engine although the cause for limitation and the allowable performance changes may vary with different engine designs.

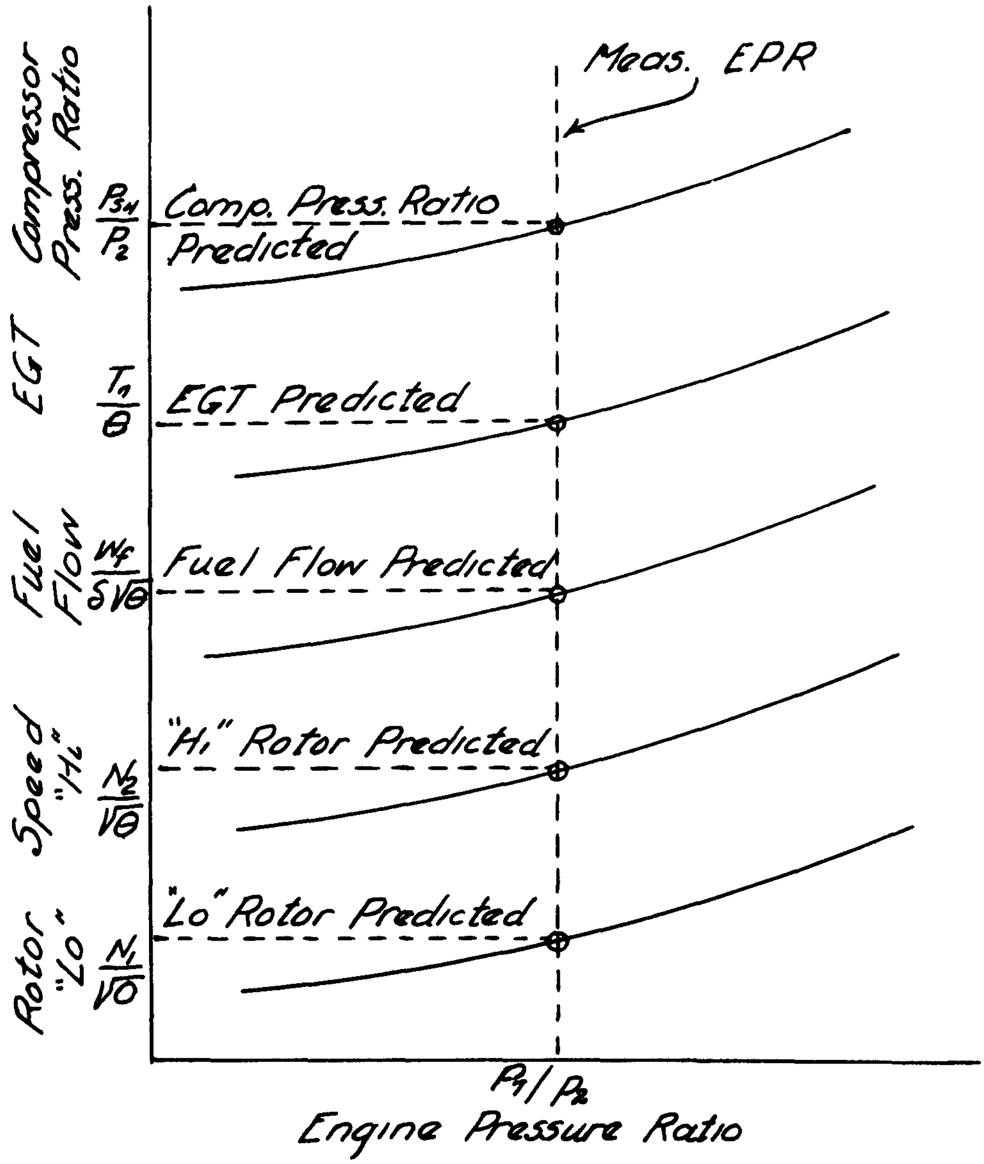
The above discussion was given to describe the fundamentals of the single spool variable geometry engine analysis. Detailed derivation and discussion of Reynolds Number effects, bleed air extraction, etc., are given in Appendix I.

2.4.2 <u>Twin Spool Engine Performance Analysis</u>

The twin spool engine analysis method uses a comparison of predicted and measured gas generator characteristics to indicate a change in the engine performance. Theoretically the same analysis procedure can be used on the twin spool engines as described for the single spool engines, however, more measurements of interstage pressures and temperatures are required to provide a solution of the matrix. Provision for these measurements is not generally available on production engines, and in the opinion of Pratt & Whitney, manufacturers of twin spool engines, the complexity of the interactions of the two rotor system make the EGT comparison method of analysis impractical to apply.

The analysis method proposed for the twin spool engine is based on the approach described in Pratt and Whitney Gas Turbine Information Letter No. 15. In this procedure "predicted" values of engine rotor speeds, fuel flow, exhaust gas temperature and compressor pressure ratio are compared to measured values of these parameters. The predicted values of the parameters are determined from curves based on the performance of an "average" engine. These curves are illustrated in Fig. 4 below. The difference between the value of the parameter predicted from the measurement of pressure ratio, and the value of the parameter as measured on the engine is an index of deviation of a specific engine from the average, or generic engine.

Fig 4
Twin Spool Engine
Generic Performance Curves



This difference, unless it is large is generally not significant since variations in components and adjustments cause engine to engine differences. Changes in these differences of measured and predicted values of the parameters are indicative of changes in the thermodynamic performance of the engine, and are used as a measure of engine deterioration.

Plotting the changes in difference between predicted and measured values vs. time shows any gradual deterioration or sudden change in performance. Extropolation of the trend of these measurements until they reach a limit provides an estimate of the total life remaining in the engine.

Establishing the allowable limits on the parameter changes was done based on correlation of inspection findings from test cell engine operation and engine user experience. These limits require verification by operational test as do the theoretically derived limits for the single spool engine.

Isolation of the cause of the malfunction is obtained through recognition of the pattern of the changes in the parameters. For instance, decreasing values of N_1 and N_2 with increasing fuel flow and EGT is in general indicative of first stage turbine seal erosion. Increasing N_1, N_2 and fuel flow with decreasing EGT is indicative of a change in exhaust nozzle area, while increasing N_1 fuel flow and EGT with decreasing N_2 shows nozzle guide vane bowing. Simultaneously occurring deteriorations are not easily separable through a logic system, however there is no known combination of deteriorations that will give no change in all of the gas generator characteristics, thus the general condition of the engine is revealed through changes in the parameters.

The above discussion was given to describe the fundamentals of the twin spool fixed geometry engine analysis. Detailed discussion and procedure for application are given in Appendix I.

2.4.3 Lubrication System Analysis

The lubrication system is a subsystem that historically has been troublesome on all engines. The problems are mainly in the form of leaks or contamination that reduces oil flow to the required areas, and problems with the venting and oil seal pressurization. The faults are usually detected by visual observation of external oil leaks, excessive oil consumption, and changes or fluctuations in oil pressure.

Two different lubrication systems are in common use. One system uses a pressure regulator to maintain an essentially constant pressure on the oil distribution system. The second system does not regulate the pressure except as a safety precaution at extreme overpressures. The methods of providing early warning of distress in these two systems necessarily differ in detailed implementation although the fundamental concepts used are the same.

Basically, the flow-pressure relationship in an hydraulic system is established by the characteristics of the fluid (density, viscosity, etc.) and the resistance of the piping system. It is this flow-pressure relation that is used to detect changes in the lube system performance that are indicative of distress. For instance, leaks in the piping system result in a decreased resistance to flow. In a regulated pressure system this decrease in resistance will be translated into an increased flow, while in an unregulated pressure system (i.e., constant flow) it will be translated into a decreased pressure.

The measurements required for the lube system analysis are given in Table 9 below.

Table 9

Lube System Measurements

	Unregulated Pressure System	Regulated Pressure System
1.	Oil Press.	Oil Press.
2.	Oil Temp.	Oil Temp.
3.	Engine Speed	
3.		Oil Flow
4.	Sump Press.	Breath Press. Diff.
5.	Tank Press.	Scavenge Oil Press.
6.	Oil Consump.	Oil Consump.

Measurements 1, 2, and 3 are used to calculate the corrected oil pressure or oil flow, which is plotted vs. time to show long time deterioration trends or sudden changes. In general, it is anticipated that this measurement will detect clogging of lines or nozzles the equivalent of about one half or more of the smallest nozzle, which should be adequate for early warning since the lube system redundancy generally provides the capability of operating with one nozzle plugged.

Measurements 4 and 5 detect seal leaks, vent line restrictions, vent valve malfunction, etc.

Measurement 6 is the most sensitive one available for detection of leaks and although the pressure measurements will show relatively large leaks the oil consumption is far more sensitive for detection of this fault.

2.4.3.1 Unregulated Pressure Lubrication Systems

In the unregulated pressure lubrication system, a constant displacement engine driven pump provides oil to the piping and distribution system. The quantity of oil supplied is directly proportional to engine speed, thus the oil pressure will be a function of engine speed. The character-

istics of the lubricant (i.e., viscosity, density, etc.) are related to the oil temperature thus the pressure will also be a function of temperature. Standardizing, or correcting the measured oil pressure for engine speed and oil temperature provides a reference that is dependent only upon the distribution system and pump characteristics and thus can be used to detect changes in these components that are indicative of trouble.

For the unregulated pressure system, the corrected oil pressure is given by the equation

$$P_c = P_m \left(\frac{N_o}{N_m}\right)^2 \left[\frac{1}{1+\beta(T_o - T_m)}\right]$$

where P_c is corrected pressure
P_m is measured pressure
N is engine speed
T is oil temperature
β temp. coeff. of density of the oil
Sub o refers to standard condition
Sub m refers to measured condition

A complete derivation of this equation is given in Appendix 2.

2.4.3.2 Regulated Pressure Lubrication System

In the regulated pressure lubrication system a constant displacement pump supplies oil to the distribution system through a pressure regulator that bleeds some of the discharge oil back to the pump inlet to maintain a constant pressure on the distribution system. In this system, the oil pressure is indicative of the pressure regulator

performance, and to infer lube system condition requires the measurement of oil flow. The oil flow is a function of oil pressure (which is regulated). The characteristics of the fluid (i.e., viscosity, density, etc.) are functions of oil temperature, thus the oil flow will also be a function of temperature. Standardizing, or correcting the measured oil flow for pressure regulator droop and temperature provides a reference that is dependent only upon the lubrication distribution system and thus can be used to detect changes in it that are indicative of trouble.

For the regulated pressure system, the corrected oil flow is given by the equation

$$q_c = q_m \sqrt{\frac{P_o}{P_m}\left[1+\beta(T_o-T_m)\right]}$$

where
- q_c corrected oil flow
- q_m measured oil flow
- P oil pressure
- T oil temperature
- β temp. coeff. of density of oil
- Sub o refers to standard condition
- Sub m refers to measured condition

A complete derivation of this equation is given in Appendix 2. If a perfect pressure regulator were used the P_o/P_m term of the equation would equal one. However, the pressure regulators in general have a "drooping" characteristic such that the pressure is not absolutely constant over the flow range. This droop in the regulator has been used to infer some lube system problems. It is not as sensitive to changes in the piping system as the corrected flow measurement proposed above.

2.5 Analyzer Accuracy

This section summarizes the methods and data used in estimating the accuracy of the various systems of engine analysis, and the method of data smoothing. Detailed discussion and derivation of the equations is given in Appendix 3.

2.5.1 Analyzer Accuracy Criterion

Analyzer accuracy is the ability to distinguish between engines that are operating within the acceptable limit of change of the degradation parameters and those which have changed more than the allowable limit. An analyzer "error" is an erroneous indication in which the engine is shown to be outside of an acceptable limit (i.e., bad) when it is really inside the limit (i.e., good) or vice versa. The criterion of accuracy used in this analysis is the probable, or mean number of tests between erroneous indications. This is analgous to the "mean time between failure" criterion in reliability analysis.

The "errors" or erroneous indications arise because the measurement and computation of the deterioration parameters are notperfect, thus repeated measurements will not be exactly the same value even if the item being measured has not in reality changed. If this variation of the measurements is small compared to the allowable limit, then an "accurate" analyzer is obtained. If, however, this variation in measurement is large compared to the allowable limit, then an "inaccurate" analyzer is the result.

To estimate the accuracy of the analyzer systems, studies of the variation of the measurements caused by sensors, transducers, recording, and computation were made to arrive at an estimate of the total variance and standard deviation of the deterioration parameters. Comparison of these variances with the allowable limits provides an estimate of the probable measurements inside and outside of the limits for any assumed condition.

The results of this comparison are shown in Table 10 below, for assumed conditions of a new engine, 50 percent deteriorated, and 75 percent deteriorated. The percentage deterioration means that the actual value of the parameter has changed by this percent of the allowable limit.

TABLE 10

ENGINE ANALYSIS METHOD ACCURACY

Engine Condition →		New		50% Deter.		75% Deter.	
Data Acquisition →		Man	Auto	Man	Auto	Man	Auto
Engine Component	Data * Location	Reading per "bad" reading Single Spool Engine					
Compressor	gb	3	7	3	4	2	3
	ab	3	22	3	6	2	3
Turbine	gb	21	71	6	9	3	4
	ab	21	1000	6	19	3	5
Combustor	gb	1000	1000	50	100	7	8
	ab	1000	1000	31	380	6	12
Deterioration Parameter	Data Location	Reading per "bad" reading Twin Spool Engine					
Rotor Speed	gb	30	36	7	10	3	4
N_1	ab	27	230	7	13	3	4
Rotor Speed	gb	22	190	6	12	3	4
N_2	ab	22	240	6	17	3	5
Ex. Gas Temp.	gb	26	47	6	8	3	4
T_7	ab	22	190	6	12	3	4
Fuel Flow	gb	19	90	6	9	3	4
W_f	ab	82	32	4	7	3	3

* ab - airborne data acquisition
gb - ground based data acquisition

Exact limits for an acceptable engine analyzer cannot be definitely established because there is no hard and fast line below which some benefit may not be obtained from the analyzer. However, a probable erroneous indication in every four or five tests is obviously unsatisfactory while an erroneous indication every thousand tests can certainly be considered excellent performance.

Inspecting Table 10, it is seen that both twin spool and single spool engines deteriorated only 75% would be called "bad" from 25 to 50%

of the time (i.e., 2 to 4 readings per "bad" reading). Conversely, engines with 125% deterioration (i.e., 25% past the limit rather than 25% inside the limit) would be called "good" from 25 to 50% of the time.

Such performance of an analyzer system cannot be considered acceptable. Fortunately there are several methods available for smoothing these random variations so that much better performance can be obtained from the system.

2.5.2 <u>Data Smoothing</u>

The fundamental problem in engine analysis is that of obtaining the best estimate of engine condition based on results of a sequence of tests. If the measurement accuracy is very high relative to the tolerance limits, it is obvious that the most practical and realistic estimate of the engine conditions is the indication of the last test, ignoring previous test results. On the other hand, if the error standard deviation is large compared to the tolerance limit, the probability of an erroneous indication is high.

A practical smoothing of these random measurement variances may be obtained by weighting the test data in accordance with how recently it was acquired to obtain a "weighted" average of all of the test data taken. One weighted average of the data is known as the "geometric moving average" or "logarithmic average" of the sequence of indications." This average is similar to the data obtained in "cumulative summation charting,"- a statistical quality control technique that has been in use for some time.

The logarithmic average data smoothing technique treats the data in such a way that the average value used for plotting the deterioration of the engine depends upon past measurements but is weighted more heavily by the recent values than by the older ones. The procedure for arriving at the logarithmic average is a very simple one to follow either with manual calculation or in a computer operation. The algebraic expression for the logarithmic average is:

$$\bar{X}_n = \bar{X}_{n-1} + \alpha(X_n - \bar{X}_{n-1})$$

where $\bar{X}$ = log average of n tests

$\bar{X}_{n-1}$ = log average of previous test

X_n = value of parameter determined at n th test

α = smoothing factor

The value of α may be selected as any fraction less than unity. The smaller the value of α the smaller will be the variance of the log average and the slower the log average will respond to any change in the level of the measurement. The relationship of the standard deviation of the log average to the standard deviation of the original data is given by the expression:

$$\sigma_{\text{log ave}} = \sqrt{\frac{\alpha}{2-\alpha}}\,\sigma_{\text{original}}$$

For estimating the effect of data smoothing on analyzer accuracy a value of α of 0.1 was chosen, since this value provides a reasonable response to sudden changes and a reasonable variance suppression. The accuracy of the analysis methods using this data smoothing technique are shown in Table 11 below.

TABLE 11

Engine Analysis Method Accuracy with Data Smoothing

Engine Condition		New		50% Deter.		75% Deter.	
Data Acquisition		Man	Auto	Man	Auto	Man	Auto
Engine Component	**Data Location**	**Reading per "bad" reading Single Spool Engine**					
Compressor	gb	1000	1000	106	1000	8	20
	ab			106	1000	8	65
Turbine	gb			1000		70	1000
	ab					70	
Combustor	gb					1000	
	ab					1000	
Deterioration Parameter	**Data Location**	**Readings per "bad" reading Twin Spool Engine**					
Rotor Speed	gb	1000	1000	1000	1000	100	350
N_1	ab					78	1000
Rotor Speed	gb					78	780
N_2	ab					78	1000
Ex Gas Temp	gb					86	180
T_7	ab					145	780
Fuel Flow	gb					61	280
W_f	ab					23	110

Inspection of Table 11 shows that excellent performance of the analyzer system can be achieved without question with up to 50% deterioration of the engines. At 75% deterioration, some of the numbers are lower than desirable. However, it must be remembered that the value of the smoothing factor was arbitrarily selected, and that modification of this factor can change these estimates markedly. With proper data smoothing, it seems that any of the four methods of data acquisition can provide a sufficiently "accurate" analysis so that this need not be a factor in selecting an engine analyzer.

The lag of the log average in indicating a sudden change in the parameter level is a disadvantage, since if a sudden change in engine performance occurred the log average does not show this immediately, and this increases the probability of accepting a "bad" engine. For the variance suppression of the engine analysis procedure this is not a serious factor as demonstrated by the following illustration.

Assume an engine operating with one of the parameters at 75% of the limit (i.e., three quarters of its life used) some sudden change in the condition takes place such that the parameter moves to 125% of the limit (i.e., it is as far outside the limit as it was inside the limit before the change). On this basis, it will require six more data points after the changes to bring the log average from the 75% to 100% point (i.e., six readings to show out-limit performance). However, it should be evident after the third reading that a change in performance had very likely taken place and after the fourth reading this would be practically a certainty.

If the log average smoothing technique had not been used, then about one reading in every four on this same engine would be indicating an out-limit performance before the sudden deterioration had taken place, thus, a single

reading outside the limit cannot be accepted as a rejection criteria.

The probability of two successive readings being outside the limit if the engine were really 75% deteriorated (or conversely being inside the limit if the engine were really 125% deteriorated) is one in sixteen. Even this is too great a probability to use for rejection. The probability of three successive readings outside of limits if the engine were really good is 64, which is low for a rejection limit but probably satisfactory since the assumed engine is three quarters deteriorated. Thus, without the log average smoothing, three readings would be required with the engine really outside of limits before there was reasonable assurance that this was the fact.

Comparison of the data treated by the smoothing technique and not treated shows that, with the data variance and limits as defined, it is necessary to obtain at least three outlimit data points before being assured of outlimit performance, and that both smoothed and unsmoothed data can provide this capability. The log average data plot, however, shows the long-range trend so much more clearly, because of the variance reduction, and eliminates the confusion of accepting for several flights, engines that show outside of limits, hence it should be used. Other data variance reduction methods than the log average have been investigated and rejected because of the complexity of the calculation procedures required to use them with no real advantage in their use.

A "moving average," in which a specified number of the last points are averaged is one means of data smoothing. The application of this method requires the storage of the specified number of points and the dropping of one point each time a new point is added. The performance of the moving average is similar to the log average. Using the last 20 points of data for the av-

erage would provide about the same variance suppression as the $\alpha = .1$ in the log average and would require about eight readings to give an outlimit performance on a change from 75% to 125% of the limit - a little more lag than the log average.

Approximating the slope of the best straight line through a specified number of the last points was considered, but the calculations to arrive at the best straight line through the "least squares" method is far too complex and time consuming a procedure if any other satisfactory method can be developed.

2.6 Non-Recommended Measurements

This section describes two areas of measurement on jet engines where it is not generally practical to make measurements for early warning of malfunctions.

2.6.1 Control and Accessory Area

Table 2 of this report indicates that the Control and Accessory area of the jet engine is responsible for many more of the in-flight power loss events than the main engine. However, this area is generally not amenable to standardized measurements because (1) the controls are usually servo systems that compensate their input-output relation for deterioration and external conditions - somewhat analgous to radio circuits that operate very satisfactorily with wide ranges in tube or transistor characteristics, (2) measurement of the significant items such as valve or follow-up positions would require redesign of the controls to add the appropriate sensors, (3) the controls have had extensive reliability development to the extent that in many cases they are more reliable than the instrumentation system that would be used to measure them, hence the measurement would only increase their unreliability, (4) control and accessory problems are usually associated with a particular component that becomes the subject of intensive product improvement programs whenever a chronic fault is discovered.

For these reasons, although standardized C&A measurements are not desirable, the data acquisition system of an engine analyzer should have enough empty channels and sufficient flexibility so that control and accessory problems can be monitored appropriately for various aircraft - and the monitoring be kept up-to-date with the current engine problems.

2.6.2 Transient Performance Analysis

As a part of this study of Jet Engine Analysis, an investigation was undertaken to determine the effectiveness of using transient engine performance to measure the condition of components and predict deterioration rates. Although appearing more complex than steady state performance, the transient performance of the engine, being controlled by the difference of two large torques (compressor and turbine) offers certain advantages in sensitivity, and provides dynamic control information and engine margin information not contained in the steady state performance.

To investigate the practicality of transient performance analysis, a computer model of a J79 engine was subjected to a simulated throttle burst from idle to military power setting, and the transient performance of key parameters was recorded. This procedure was done with the computer model of the engine representing a "new" engine, and with various degrees of deterioration in the major functional components such as the compressor, combustor and turbine.

From the study of the transient response of various parameters of the engine, it was found that external ambient conditions of pressure and temperature modified the transient performance a great deal more than the deterioration it was attempting to detect. No practical method of controlling the ambient conditions in other than a test cell could be conceived, and no "correction" of the transient performance to a reference condition was found. Thus it is concluded that although transient performance analysis is a valuable and powerful tool for engine design and development where controlled test conditions are available, it cannot be used effectively as a maintenance tool.

2.7 Engine Analysis Methods Comparison

This section compares the four methods of engine analysis that can be obtained through the combinations of ground based or airborne data acquisition either manually or automatically. The comparison is made to select a system for evaluation of the four areas of engine measurement which the study has indicated have significant potential in determining engine condition. These four areas of measurement are

1. Vibration
2. Time Temperature
3. Lube System Contamination
4. Performance Sensitive Parameters

The report has outlined the status of each of these major areas and the study has developed a means of using the performance sensitive parameters as one of the tools of engine analysis.

The criteria to be considered in the selection of an analysis method for evaluation in the next step are:

1. System accuracy
2. System comprehensiveness
3. Time to get started
4. Estimated size or weight of equipment
5. Suitability for operational use

Table 12 below presents a summary of the comparison of the methods with respect to each of these items, and the following paragraphs give a brief discussion of the comparison. From this table and the discussion,

it is quite evident that automatic airborne data acquisition is the general system that should be evaluated, since it provides the ability to evaluate for comparison all of the other systems.

Table 12

Engine Analysis Method Comparison

Engine Analysis Method: Data Acquist. Location	Engine Analysis Method: Data Acquist. Method	Accuracy	Start Time (Months)	* Weight of Equipment Req'd (lbs): Airborne	* Weight of Equipment Req'd (lbs): ** Ground	Evaluation Comprehensiveness
Ground	Manual	OK	2-4	30	***	Uns.
Ground	Automatic	OK	12-15	30	800	Uns.
Airborne	Manual	OK	3-6	45	***	Poor
Airborne	Automatic	OK	15-18	175	1700	Good

* Based on four engines instrumented.

** Estimated weight of Ground Based Equipment.

*** Manual computation requires no equipment.

2.7.1 Analysis Method Accuracy

Tables 10 and 11 of Section 2.5.1 show that the accuracy (i.e., the ability of the system to indicate engine condition correctly) of each of the methods is comparable, and with proper data smoothing is adequate for the purpose. Thus, the selection of a method for evaluation of the concepts and for final use can be made based on criteria other than accuracy.

2.7.2 System Comprehensiveness

For evaluation, it is desirable to be able to compare the effectiveness of as many of the systems as possible, so that sound judgment can be exercised in selecting the method for particular applications. The size, weight, or operational use of some aircraft may well preclude the possibility of using data acquisition and analysis methods on one kind of airplane that are quite feasible on another type.

The system which provides for the most comprehensive evaluation is airborne automatic data acquisition with continuous recording of measurements about e.ery 5 to 10 seconds. This system will provide evaluation of the continuous recording of information. By selection of portions of the data, intermittent data acquisition can be evaluated, as well as the advantages of short time averaging. Selection of single readings will provide evaluation of airborne manually acquired data methods, and operation of the airborne system on ground run-up of the engines will provide evaluation of the ground based engine analysis methods.

2.7.3 Time To Start

The time required to start an evaluation is an important item to consider, sinca a program delayed too long can be worthless. The manually acquired data methods certainly provide the shortest starting time, since very little equipment additions to either the airplane or the ground operations are required. They have an additional advantage in that more airplanes could be included in the evaluation because of the minimal equipment requirement. However, they provide only limited data

acquisition, lack the ability to evaluate automatic data acquisition methods, and require attention of the flight crew periodically.

2.7.4 Estimated Equipment

The equipment required, particularly the airborne equipment, may be the determining factor in selecting the engine analysis method on some airplanes, since the room for the equipment may not be available.

The manual data acquisition systems have such marked advantages over the automatic data acquisition systems in this respect that their use may be dictated on some airplanes. Other general features of the manual data acquisition systems were covered in the preceding paragraph.

2.7.5 Suitability for Operational Use

Throughout the study, continual consideration has been given to the operational use of the engine analyzer in a final configuration. It is believed that any one of the four basic data gathering systems can be operationally practical, although specific methods of integrating the concepts into the Air Force information system is beyond the scope of this study.

No detailed specification of the configuration of an operational engine analyzer has been defined, although engine analysis measurement requirements have been sufficiently defined in order to form a development specification for the Turbojet Engine Analyzer. The requirements of the engine analysis will be quite different from airplane to airplane, since the particular problems that assail different airplanes may be detected best by different measurement areas.

In spite of the "individualised" nature of the engine analysis problem however, a general consideration of the overall requirements and a concept of a final configuration of an engine analysis system must be kept in mind during the evaluation work as it has been during the study.

In general an engine analysis system should be capable of

1. Evaluating the quality of existing engine performance.
2. Predicting malfunctions or detecting them before they become catastrophic.
3. Predicting engine life remaining.
4. Providing information to meet the turn around time of the application.
5. Providing a permanent record of engine history.
6. Operating with minimum flight crew attention.
7. Operating with a data reduction system.
8. Recording for sufficient time to meet the requirement of the application.
9. Providing a record of engine operating time.
10. Operating with a 1 minute warm up.
11. Protecting records through crash and fire.

The following paragraphs provide a brief discussion of each of these general requirements.

Evaluation of the quality of existing engine performance is provided by a comparison of the measurements of present performance of the engine with its original performance when new or from overhaul. Comparison against a fixed value is not possible, since individual engine variations from the average of all engines of a given model are too large in comparison to the limit of change that is indicative of poor performance.

Recognition of changes in performance in the four general areas of performance sensitive measurements, vibration, time temperature, and lube system contamination provide a good index of the quality of the present performance.

Predicting malfunctions or detecting them before they become catastrophic is provided by the same comparison as the performance quality evaluation. Quantitative interpretation of this information is required to evaluate properly the severity and consequence of changes in performance. Tentative limits on the basis of mathematical engine models or experience have been developed for the performance sensitive measurements. These limits require verification by practical experience. Limits on the non-performance sensitive parameters of time temperature and lube system contamination are generally unknown and require development. Tentative limits on broad band vibration measurements are available from the engine manufacturers for each engine model. Limits for the signature and tach ratio method require much further development. Furthermore, the ability to predict a malfunction or detect it depends upon the malfunction providing a measureable change in performance before it becomes catastrophic. To date there is no data to indicate how many of the malfunctions occurring actually do this, because there has been very little correlation of malfunctions vs. chronological records of engine performance. This data must be obtained before any reliable estimate of the value of any facet of engine analysis can be made.

Predicting engine life remaining is done by trend analysis of the performance quality evaluation information. The prediction is made by extrapolating the curve of performance quality vs. time until the extrapolation curve intersects a limit. This life prediction is based on the

assumption of a constant deterioration rate at the value shown by the trend. Since it has been demonstrated that most of the events and malfunctions in jet engines occur randomly with time, the life prediction cannot be considered highly reliable.

Providing as short a turn around time as possible is necessary to maintain a high "alert" status of the fleet. This should not be a factor in the program for the next step in engine analysis, since this program is basically to evaluate, in retrospect, the performance of the various facets of engine analysis in predicting the events that do finally take place. Table 13 compares estimates of the turn-around time for three general analysis methods, ground data acquisition, airborne data acquisition, and a limited analysis. Many variations on each scheme are possible, the times estimated for each operation are an average time consistent with the general kind of operation envisaged as possible for a final engine analyzer system. The times do not include allowances for vibration signature nor lube system contamination analysis.

TABLE 13

Turn Around Time Estimates

Operation	Ground Data Acquisition	Airborne Data Acquisition Complete	Airborne Data Acquisition Preliminary
	Estimated Time, Hours		
1. Prepare Craft	0.5-1.0	0.0	0.0
2. Acquire Data	0.3-0.4	0.0	0.0
3. Reduce Data	0.1-0.5	0.05-0.3	0.05-0.1
4. Plot Data & Decision	0.3	0.3	0.05-0.1
5. Data Transp.	0.0-0.2	0.2	0.2
TAT 1 Engine	1.2-2.5	0.55-0.8	0.3-0.4
TAT 4 Engines	3.3-6.0	1.6-2.6	0.6-1.0

In Table 13 preparing the aircraft includes towing to and from an engine run-up area, connecting equipment, starting the engines, etc. Acquiring data includes stabilizing the engine and recording the data. Reducing the data includes performing the calculations to standardize the parameters and comparison with the initial performance. Plotting the data and making the decision is plotting the last performance indications on the trend chart, and making a judgment based on the indications. Data transport is taking the data from the airplane to the data reduction area. The range of times encompass the various schemes of manual or automatic data acquisition and calculation.

Providing a permanent history of the engine is accomplished by storing the data of the trend analysis.

Requiring minimum flight crew attention is provided by automating airborne data acquisition where used.

Operating with a data reduction system is a "must" to achieve the turn around times of Table 13, since the comparisons and computations involved while simple enough to be performed manually are too time consuming. The data acquisition system must be designed to complement the data reduction system to provide the best overall performance. PCM multiplexed recording of data on magnetic tape is the optimum method of maintaining accuracy, size, and minimum equipment complexities. The data acquisition system and data reduction equipment should use the same code if possible, although translating units from a binary code to the binary coded decimal system used by some computers is not a severe handicap. Recording in binary coded decimal language requires additional size and weight in the airborne equipment which would be desirable to

avoid if possible.

Recording for sufficient time to meet the application requirement can be accomplished with enough tape capacity in the tape transport. A continuous record of the engine parameters, (i.e., recording every 5 or 10 seconds during time of engine operation) while desirable in the evaluation program, may very well turn out to be unnecessary to perform the required functions of engine analysis. This requirement should be reviewed in the light of the evaluation program findings, since very significant reduction in the size and weight of the tape transport can be made if intermittent data acquisition can be used.

A continuous record of time, to indicate when in the engine's life a particular piece of data was acquired, is necessary to make the trend plots which are the best way of detecting or predicting malfunctions. This can be performed by recording a clock reading every frame in an automatic data acquisition system.

Operation within one minute of turn-on is well within the capability of current data acquisition systems.

Protecting records through crash and fire is another requirement that should be examined carefully in the light of the findings from the evaluation program. If the data acquisition system for the engine analyzer is only required to provide data to assess the condition of the engine and detect or predict possible malfunctions, then protection of the data in the event of crash may not be of primary importance. If, however, in addition to engine analysis the data acquisition system is intended to perform the functions of post crash analysis, then the fire and crash resistance along with continuous data acquisition become paramount. We do not currently know of a tape recorder that will withstand crash and fire

without a great deal of development. However, its development seems possible through the use of high temperature components and sublimating protective housings.

2.8 Evaluation Configuration

This section outlines a general system for evaluation of the engine analyzer concepts. As pointed out previously, the definition of an operational engine analysis system will depend very largely on the capabilities, use, and limitations of each aircraft type, hence a rigid specification should not be attempted. The purpose of the evaluation program proposed is to compare as many of the procedural variation in collecting and analyzing data as possible to provide a sound basis for selecting an operational engine analyzer system for each application.

For this purpose, as previously stated, an automatic airborne data acquisition system taking measurements continuously provides the ability to evaluate all of the combinations of data collection and processing. Although this configuration is proposed for the evaluation program, it seems probable that for purposes of engine analysis, data recorded every two to ten flight hours or even longer intervals will be quite satisfactory. The evaluation program will establish a basis for determining the proper recording interval.

The total complex of engine analysis equipment can be considered in three categories, (1) sensors (2) data acquisition and recording and (3) computing. The following paragraphs discuss each of these categories with respect to the recommended evaluation programs and an operational engine analyzer system as it is presently seen. The equipment described is typical of the equipment required for either operational use or evaluation. In general it can be assembled from components that are current "shelf" items.

2.8.1 Sensors

The measurements it is necessary to make for the engine analysis determine the sensors it is necessary to use. Listed below in Table 14 are the measurements it is necessary to make in the evaluation program. In general, the current state-of-the-art of high quality sensing techniques and equipment are satisfactory for the measurements. The accuracy of such equipment was the basis of the accuracy estimates, for the engine analysis system, discussed in paragraph 2.5 above.

On specific aircraft it may be necessary to measure other items than those listed in Table 14. The data acquisition system should have "empty" channels available for miscellaneous measurements of this kind to adapt to particular test vehicles.

TABLE 14

Engine Measurements Required

Measurement	Symbol	System Error Limit*		Comments
		Total Error Limit	Repeat-ability	
1. Comp. Inlet Total Pressure	P_2	3.0	2.5	Used for standardizing or correcting other measurements
2. Comp. Inlet Total Temperature	T_2	1.5	1.0	
3. Comp. Bleed Air	Wb/Wa	1.5	1.0	
4. Engine Speed	N	1.0	0.8	N_1 & N_2 on twin spool engines
5. Engine Pressure Ratio	EPR	2.0	1.5	P_5/P_2 single spool P_7/P_2 twin spool
6. Compressor Static Pressure Ratio	CPR	2.0	1.5	P_{s3}/P_2 single spool P_{s4}/P_2 twin spool
7. Fuel Flow	W_f	3.0	2.0	
8. Ex Gas Temp	EGT	1.5	1.0	T_5 single spool T_7 twin spool
9. Oil Pressure	P	3.0	2.0	
10. Oil Flow	W	3.0	2.0	Reg. Press System only
11. Oil Temperature	T	3.0	2.0	
12. Oil Sump Pressure	P	3.0	2.0	Scavenge oil pressure in Reg. Pressure System
13. Oil Tank Pressure	P	3.0	2.0	Breather Pressure in Reg. Pressure System
14. Oil Consumption				
15. Vibration		Detect changes of 0.2 mils 20 cycles to 2.0 KC.		

* Error limits are 2σ values expressed in percent of point.

2.8.2 <u>Data Acquisition and Recording</u>

The automatic data acquisition system described here is satisfactory for use in the evaluation program, and is typical of the kind of equipment required for engine analysis using airborne automatic data collecting.

The system is set up basically for four engines, with thirty channels of information per engine, or a total of 120 channels. This provides 12 to 15 blank channels per engine to accommodate measurements desirable on specific applications or during particular times.

Detailed design of a system will depend to a very large extent upon the instrumentation available and the test vehicle chosen. In very broad terms, the incoming analog signals from the sensors are multiplexed in a commutator where they are routed to appropriate conversion circuits. All signals are converted to a proportional time interval. During this time-interval pulses from a constant frequency source are counted to provide a number proportional to the magnitude of the sensor signal. These numbers are recorded in sequence on the magnetic tape of the recorder, so that their position in the sequence is their definition for the ground based read-out or data reduction equipment. A complete sequence requires four seconds.

Four basic signals must be accepted by the equipment for conversion to a time interval. Table 15 below lists the four kinds of signals, and the maximum number of each kind that can be handled. The total number of signals cannot exceed 120.

TABLE 15

Data Acquisition System Signal Acceptance		
Input from Sensor	Channels Available	Signal Use
1. Frequency	15	Measurement of speed from tachometer gen
2. DC Voltage	60	Magnitude proportional to measured quantity
3. AC Voltage	60	Magnitude proportional to measured voltage
4. Synchro or Second Harmonic	30	Three wire position signal proportional to measured quantity

The system can be built from shelf hardware with the exception of the commutator which will be a special assembly. State-of-the-art techniques for commutator construction are satisfactory, the number of segments and number of decks are the only variations from standards.

The recording is in binary digital form (PCM) on a magnetic tape with each data word comprising fourteen binary digits recorded transverse to the tape motion. Twelve of these digits contain the quantitative measurement information, one is used for a parity check and one is used for a timing pulse from the clock. Pulse code modulation is used to preserve the accuracy of the record independent of tape speed variations, and provide a signal directly usable by ground based computing equipment. Recording transverse to tape motion is used to minimize the analog to digital conversion gear. A complete cycle of recording requires four seconds and occupies .240 inches of tape length, which at a tape speed of .060 inches per second will provide for forty hours of continuous recording on 720 feet of tape.

In use, it is anticipated that extra tape storage units will be available, so that on landing, the tape can be removed from the airplane and replaced immediately with another blank tape. The tape storage units will provide a means for describing, by manual notation, the identification of the aircraft and engines being examined. In addition, the manual notation card will provide space for recording the lube oil servicing for inclusion in the final data.

The tape containing the raw data on the four engines will be processed through a ground based computer which will provide separate print outs of the data on each engine.

2.8.3. Computing

The computing requirements of the engine analysis procedures discussed in the previous sections must be considered separately for an evaluation program and operational use of the analyzer system. The computation procedures required are simple averaging, graph look up, subtraction, addition, and multiplication or division. These operations are so simply performed by a man, that for the evaluation program, it is recommended that equipment capable only of printing out the raw data, averaging small blocks of raw data, and printing out the average be used. This kind of operation is permissible since the evaluation programs is to correlate in retrospect engine measurements with incidents and rigid time schedules are not mandatory.

For the operational use of the engine analyzer system it is expected that intermittent data acquisition about once every two hours at the most will provide adequate information for trend analysis. This will greatly reduce the size of the airborne data recording equipment, and the quantity of data to be handled. Even with this reduction in data quantity, a ground based general purpose computer capable of handling at least a 14 digit binary word with a memory storage of approximately 4000-8000 words will be required to do the complete operations.

Some of the operations that require the large memory in the computer are the table look up of predicted values of the parameters. This is an operation that is relatively easily performed manually with adequate curves of generic engine performance but requires large memory in a computer. The evaluation programs, using manual operation in this area, will provide data on which to base a sound decision as to how much of the data reduction can be done economically with manual computation.

3.0 RECOMMENDATION

3.0 As indicated in earlier sections of this report there is no data available from which a correlation of engine deterioration or malfunction vs measured parameters can be made - primarily because no program has been inplemented in which measurements were made consistently for trend analysis. An evaluation program is necessary to determine (1) how many malfunctions give prior warning of their occurrence, and how much prior warning and (2) which of the measurement areas are most effective in detecting the malfunction or deterioration. In addition to these basic considerations, an evaluation program should also provide a comparison of the effectiveness of the four methods of data acquisition in detecting deterioration and data on the application problems consequent to each of the methods.

The program outlined in the following paragraphs provides as much evaluation of all of the facets of engine analysis as is practical to combine in a single program.

3.1 Performance Sensitive Parameters

The performance sensitive measurements it is desirable to make are listed in Table 14. The tables list the required measurement accuracy to achieve the fault detection accuracy given in tables 10 and 11. The range of measurements depends upon the application and can be specified when test vehicles are selected. These measurements should be processed by the methods described in detail in the appendix for correlation against observed malfunctions or inspection findings of deterioration.

The evaluation program for this facet of engine analysis should have measurements recorded continuously in flight, and the capability of making ground based measurements as well. This data will provide information on how many of

the observed incidents or deteriorations are reflected in the performance sensitive measurements, how many give warning of their approach, and how much warning. By comparison of single readings with average readings it will evaluate the effectiveness of manual vs automatic data requisition, and by operating during post flight ground run up of the engine it will compare ground based vs manual data acquisition.

3.2 Vibration Measurements

The program for the evaluation of vibration as an early detector of failure should obtain information to evaluate the effectiveness of the broad band and vibration signature methods. The tachometer ratio method as developed on Air Force Contracts AF34(601)-4412 and AF34(601)-9593 at the University of Oklahoma is in general more applicable to overhaul depot diagnosis than to flight line maintenance, and this approach is being developed and evaluated in other programs

3.2.1 Broad Band Vibration Measurement

The broad band vibration measurement is the only vibration measurement that is practical to make airborne This parameter may have value for cockpit presentationto prescribe engine power limitation or shutdown. Historical records of vibration may prove to be a good early warning of some kinds of failure when adequate correlation with observed events is available.

A detailed specification of the measurements depends upon the application and requires the cooperation of engine manufacturer and testing facility to select pickup locations, filter specifications, etc The vibration amplitude should be recorded continuously (once every 5 to 10 seconds) so that events revealed by inspection can be related to vibration history With twin spool engines, filtering to separate the fundamental frequencies of the two rotor systems should be incorporated The overall accuracy of the system should be incorporated. The overall accuracy of the system should be such that changes

in vibration level of .2 mil can be detected, and the pickups should faithfully reproduce the vibration from 20 cycles to 2.0 KC.

3.2.2 Vibration Signature Measurements

The vibration signature method is used only on the ground. The object of this evaluation is to obtain signatures of the engine as installed, and then approximately every 10 to 25 hours. Comparison of the signatures as the engine ages with observed incidents and inspection findings will provide the evaluation of this measurement method.

To minimize the test time required of the airplane, it is desirable to record on tape the output of the vibration pickups permanently installed on the engine for broad band analysis. To obtain a "signature," the engine must be stabilized by operating for about five minutes close to the speed of the test. During the recording the speed must be held accurately at a specified value for about two minutes while the tape recording of the pickup outputs is made. After recording, the tape can be made into a loop and played into vibration analyzing equipment without infringing further on aircraft time.

The tape recording equipment should reproduce the pickup outputs from 20 to 2000 cps with an over-all accuracy of about 1%. The vibration analyzing equipment should be capable of displaying a narrow frequency band of the tape output vs frequency over the frequency range of 20 to 2000 cps. The filter band width should be between 2 to 6% of the frequency being measured - too narrow a frequency band will give trouble with engine speed variations, too wide a frequency band will not isolate specific frequencies well enough.

It is well to note that to the best of our knowledge, this is the first time that this signature technique has been applied to early warning detection

of jet engine faults, therefore, the effort recommended here, to evaluate the method, is a pioneering effort. As such, it is subject to the uncertainties of techniques, equipment selection, and resultant interpretation that beset any new application of an existing process. We believe that the method has excellent potential for providing early detection and diagnosis of jet engine faults.

3.3 Time-Temperature Measurement

The complete evaluation of all aspects of engine ageing due to temperature and temperature transients is premature at this time since as pointed out in Par. 2.3.2 adequate definition of limits is not available, and the mode of failure, whether creep or cracking due to temperature transients, requires different handling.

A valuable start can be made in this program, however, if the continuously acquired temperature data of the performance sensitive measurement analysis is integrated through various hot section factors, and the results correlated with hot section inspections.

Definition, with assurance, of the time-temperature measurement usage will require a large mass of data on each engine model. Correlation of the data as proposed above is a step toward establishing the magnitude of the complexities involved, such as correlating effects with a temperature other than that of the component through variations of the hot section factor with temperature and/or the limit of the integral.

3.4 Oil Contamination Analysis

Evaluation of oil contamination analysis does not require any airborne measurements. The program does require careful correlation of contamination concentration with incidents and inspection observations.

Evaluation of the magnetic plug and filter examination technique of oil contamination analysis should be a parallel effort with the spectrographic analysis. The location of the plugs and number will depend largely on both the engine and the airplane since the plugs must be in an easily accessible location. Examination of the plugs and filters should be made about every ten hours, and the metallic generation per unit of time calculated and plotted chronologically.

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Appendix I

Engine Analysis through Performance Sensitive Parameters

This Appendix describes in detail the method developed to determine deterioration of single spool and twin spool jet engines from the measurement of performance sensitive parameters which are basic to the gas generator operation.

1 Single Spool Engine Performance Analysis

In general the single spool engine analysis method uses a comparison of the predicted and measured values of the turbine exhaust gas temperature (EGT) to indicate a deterioration or change in the engine performance. Through a system of quantitative logic, using these EGT comparisons, engine deterioration can be isolated to the functional components of the engine (i.e., the compressor, combustor or turbine). Simultaneously occurring deteriorations can be separated by this analysis.

The system of logic that is used to separate component deteriorations is based on the performance of an ideal engine. The characteristics of such an engine can be studied and evaluated on an engine simulator, where, by suitable computer programming, known deteriorations can be introduced and observations made on the changes in the gas generator parameters. Such a study provides data on (1) the performance of the normal, undeteriorated engine, (2) the normal engine gas generator partials and (3) the deterioration partials. From this basic data the logic system of component deterioration separation is developed. This will be shown in the succeeding paragraphs.

1.1 Normal Engine Performance Curves (Generic)

A set of normal engine performance curves are required for deterioration analysis: (a) normal flight characteristics to be used with airborne recorded data or (b) normal sea level static characteristics to be used with ground based recorded data.

a) The set of normal flight characteristics consists of three, 3 dimensional (3-D) curves which are functional relationships between certain gas generator parameters that are sensitive to several basic deterioration modes in the engine. These functional relationships are shown qualitatively in Figs. 5, 6, and 7. Corrected parameters are used in these plots to make them applicable for non-standard temperature days and for all altitudes within the operable flight regime. In addition, Reynolds' number effects have been factored into the data plots. Plotted also on each curve is the normal operation line which is used to determine reference values of the turbine discharge temperature for any given operating point. The corrected parameters and the nomenclature used in Figs. 5, 6, and 7 are defined below:

$P_{s3}' = P_{s3}/\delta_2^m$ - Corr. Compressor discharge static pressure-psia

$P_5' = P_{t5}/\delta_2^m$ - Corr. turbine discharge total pressure - psia

$W_f' = W_f/\delta_2\theta_2^n$ - Corr. fuel flow - pph

$\%N' = \%N/\sqrt{\theta_2}$ - Percent corrected speed

NORMAL ENGINE FLIGHT CHARACTERISTICS (P_{s3}')

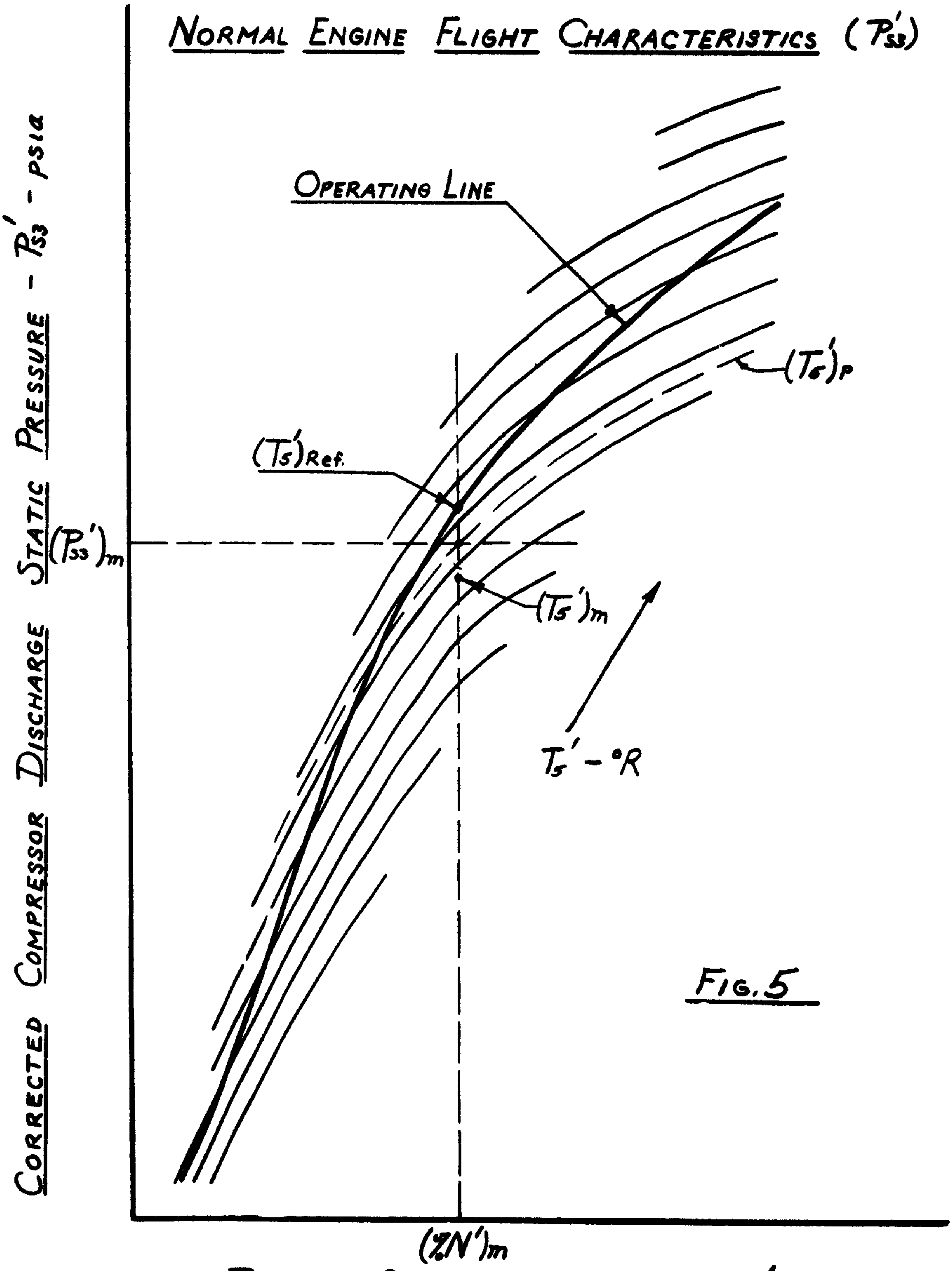

FIG. 5

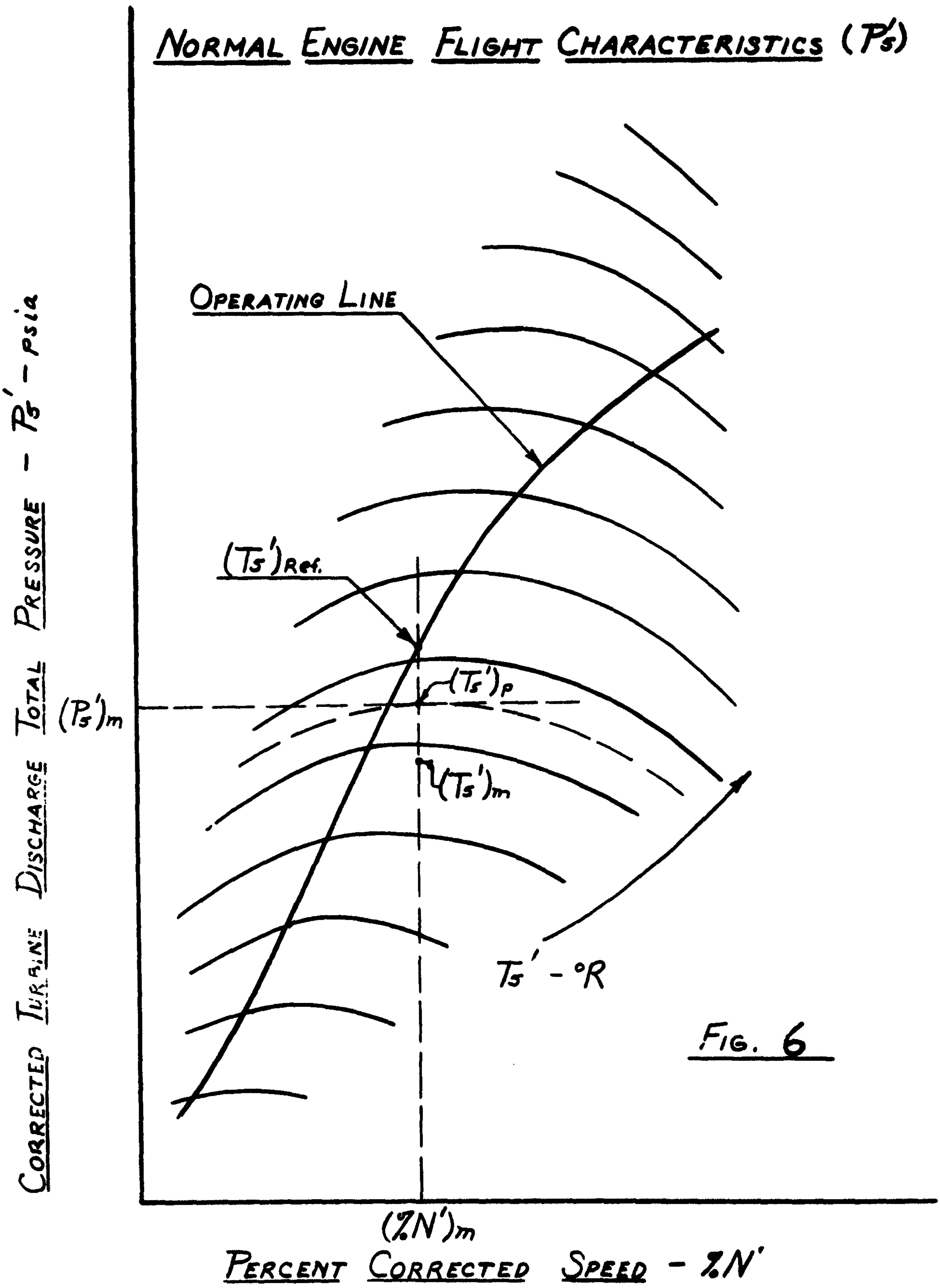
NORMAL ENGINE FLIGHT CHARACTERISTICS (P_5')
CORRECTED TURBINE DISCHARGE TOTAL PRESSURE - P_5' - psia
OPERATING LINE
$(T_5')_{Ref.}$
$(T_5')_P$
$(P_5')_m$
$(T_5')_m$
T_5' - °R
$(\%N')_m$
PERCENT CORRECTED SPEED - %N'

FIG. 6

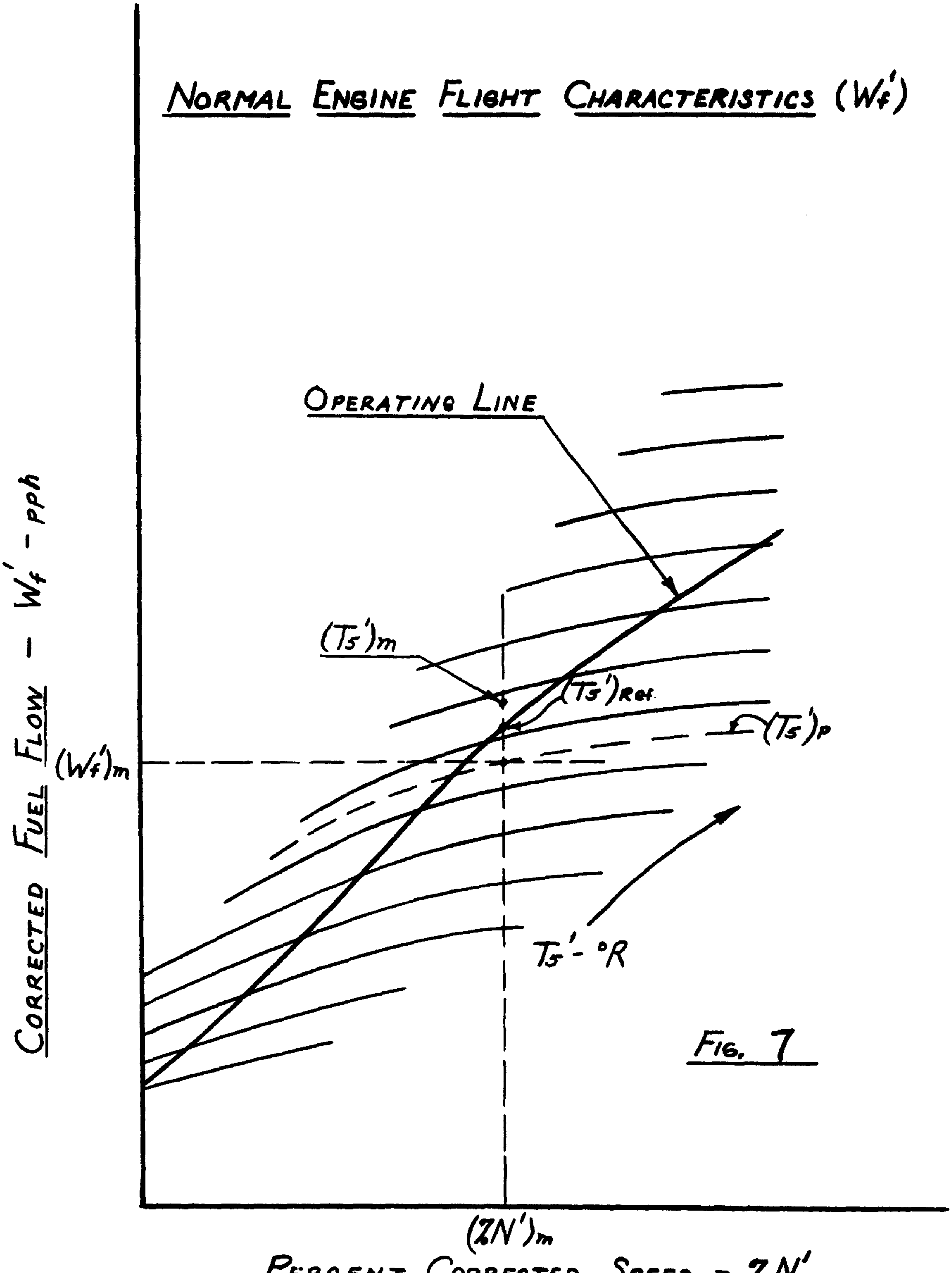
NORMAL ENGINE FLIGHT CHARACTERISTICS (W_f')
OPERATING LINE
$(T_5')_m$
$(T_5')_{Ref.}$
$(T_5')_p$
$(W_f')_m$
T_5' - °R
CORRECTED FUEL FLOW - W_f' - pph
$(\%N')_m$
PERCENT CORRECTED SPEED - $\%N'$

FIG. 7

$T_5' = T_5/\theta_2$ - Corr. turbine discharge total temperature - °R

$\delta_2 = P_{T2}/14.7$

$\theta_2 = T_{T2}/518.7$

m = exponent applied to δ_2 to introduce Reynolds' number effect

n = exponent applied to θ_2 in the corrected fuel flow expression.

Both m and n are supplied by the engine manufacturer.

$(T_5')_m$ - measured value of T_5'

$(\%N')_m$ - measured value of $\%N'$

$(P_{S3}')_m$, $(P_5')_m$ & $(W_f')_m$ - measured values of P_{S3}'; P_5' and W_f' respectively

$(T_5')_p$ - predicted value of T_5'

$(T_5')_{Ref}$ - reference value of T_5'

In use the 3-D curves of Figs. 5, 6 and 7 provide a means of comparing measured to predicted values of T_5'. For any given stable operating point, as represented by a measured value of percent corrected speed $(\%N')_m$, there will be corresponding measured values of the other four corrected gas generator parameters, namely, $(P_{S3}')_m$, $(P_5')_m$, $(W_f')_m$ & $(T_5')_m$. When these measured values that correspond to just one point of operation are plotted on their respective 3-D curves (Figs. 5, 6 and 7), a predicted value of turbine discharge temperature $(T_5')_p$ will be indicated. If there is no deterioration in the engine, the predicted and measured values

of T_s' should be equal. On the other hand if deterioration does exist in one or all of the basic engine components, then it is highly probable that each of the three predicted values of T_s' will not be equal to the measured T_s' It is to be noted also that if the predicted values of T_s' do not correspond to the reference value of T_s' , namely $(T_s')_{Ref.}$, for the same percent speed point at which the measurements were taken, it merely indicates that the characteristics of the engine under test do not exactly match the characteristics of the generic engine. This is not cause for concern since changes in the difference between predicted and measured values of T_s' are the important considerations, and the use of the generic operating line only affords a convenient means of determining a corresponding reference value of for the calculation of percentage changes. Referring to each of the 3-D curve plots, these percentage differences are formulated as follows:

$$\alpha = \left[\frac{(T_s')_p - (T_s')_m}{(T_s')_{Ref}}\right]_{P_s'} \times 100 \tag{1}$$

$$\beta = \left[\frac{(T_s')_p - (T_s')_m}{(T_s')_{Ref}}\right]_{W_f'} \times 100 \tag{2}$$

$$\gamma = \left[\frac{(T_s')_p - (T_s')_m}{(T_s')_{Ref}}\right]_{P_{s3}'} \times 100 \tag{3}$$

The subscripts outside the brackets, i.e., P_s' , W_f' and P_{s3}' identifv the equation with the applicable 3-D generic curve.

b) The set of normal sea level static characteristics consists of three, 2 dimensional (2-D) curves that are used for comparing measured with predicted values of T_2' when engine test data is acquired on the ground at an air base. For ground testing performance measurements are made at a percent corrected speed of 90%, i.e., $\%N' = 90\%$. This value of $\%N'$ was chosen so that, if the temperature of the day on which the ground test was made fell within a $0^{\circ}F$ to $120^{\circ}F$ temperature range, it would always be possible to obtain a physical speed setting that would give the percent corrected speed equal to 90%. For test operation convenience it is desirable to supply a curve based on $\%N' = 90\%$ and the above temperature range to provide the required percent physical speed as a function of the temperature of the day. Fig. 8 shows a typical curve.

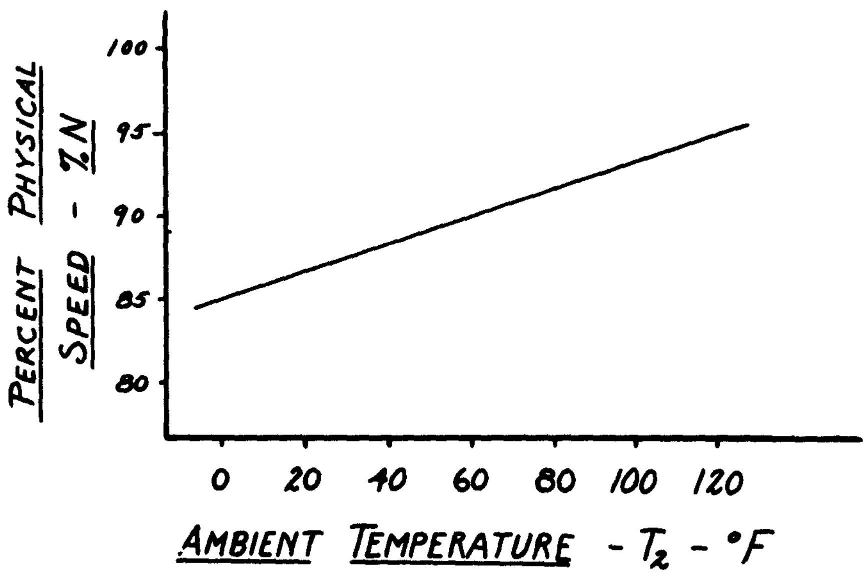

Fig. 8

Percent Physical Speed vs. T_2 for $\%N' = 90\%$

Since ground tests can be conducted at a fixed value of percent corrected speed, not only is the testing procedure simpler but the generic curves for the undeteriorated engine become less complex than those required for the airborne case. The set of 2-D curves for this case are derived from a set of 3-D curves similar to those shown in Figs. 5, 6 and 7 but represent the normal sea level static characteristics of the undeteriorated engine with no corrections for Reynolds' number effects. Entering into each one of these 3-D curves with the same value of percent corrected speed, say $\% N' = 90\%$, the deterioration sensitive corrected gas generator parameters, P_{s3}', P_5' and W_f', can now be plotted as single line functions of the corrected turbine discharge temperature T_5'. These single line plots are the 2-D curves which are qualitatively displayed in Figs. 9, 10 and 11. The nomenclature is essentially the same as for the curves of Figs. 5, 6 and 7 except that:

P_{s3}' is now equal to P_{s3}/δ_2 or P_{s3}/P_2,
and P_5' is now equal to P_5/δ_2 or P_{t5}/P_2 because the exponent (m) applied to δ_2 is not necessary.

All the comments pertaining to the use of the 3-D curves for the airborne case apply to the 2-D curves of Figs. 9, 10 and 11. Also the percentage difference equations (1), (2), and (3) are valid and will not be repeated here.

The 2-D and 3-D static and flight characteristics of a normal engine are not generally available but must be generated by the engine manufacturer for each engine model that is to be analyzed. Only one set of curves is necessary depending upon whether ground based data or flight data are to be used for the analysis.

NORMAL ENGINE SEA LEVEL STATIC CHARACTERISTICS

$\% N' = 90\%$
MACH = 0
ALT. = S.L.

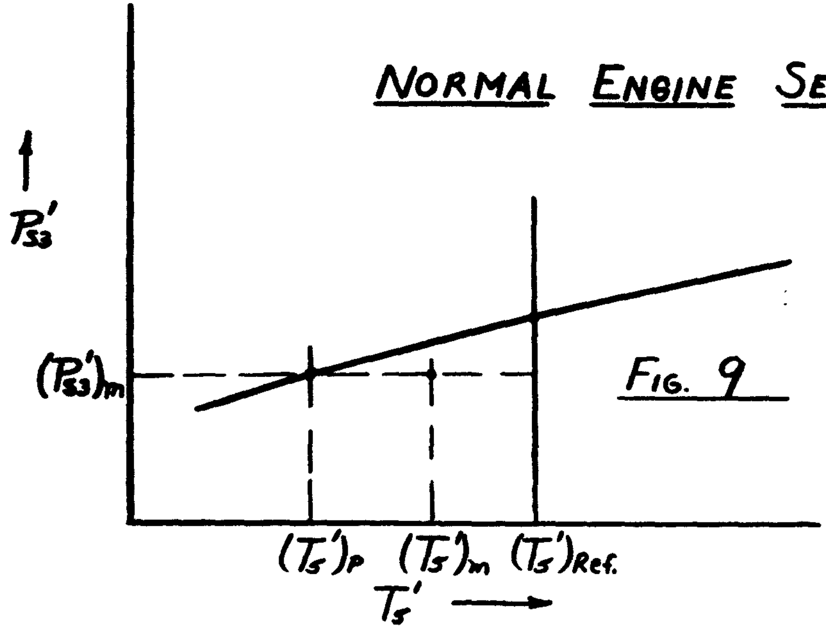

FIG. 9

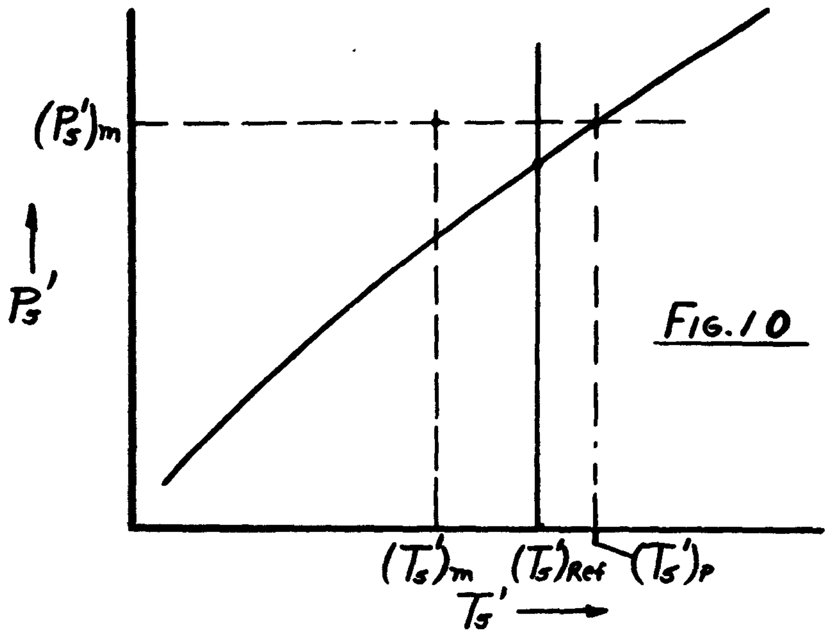

FIG. 10

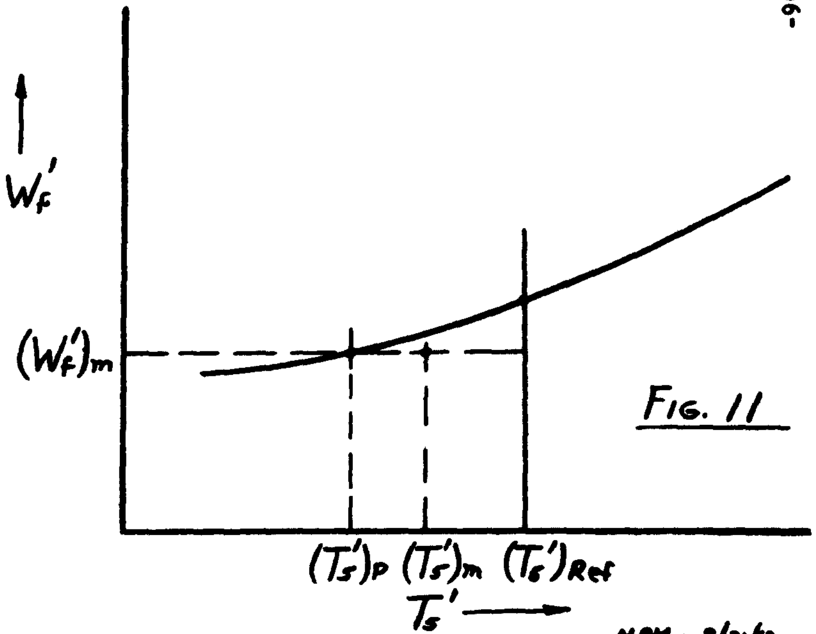

FIG. 11

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1.2 Normal Engine Gas Generator Partials

One way that is used to study the complex performance of a jet engine is to fix the operating point at some arbitrary value, vary any one or several of the controlled inputs over a small range and observe the changes in the gas generator parameters. If the induced changes in operation about a given point are small enough to be considered linear, then the resulting operation can be represented by systems of linear equations with partial derivatives relating changes in the dependent variables to the independent variables. These partial derivatives called "engine partials" are used with "deterioration partials" (described in 1.3) to form the basis of the system logic that is used in the engine deterioration analysis.

The engine partials that are involved in the deterioration logic system can be obtained from the 3-D curves of Figs. 5, 6 and 7. Any one of these curves can be used for illustration, but refer to Fig. 12, which represents an enlarged section of a typical plot.

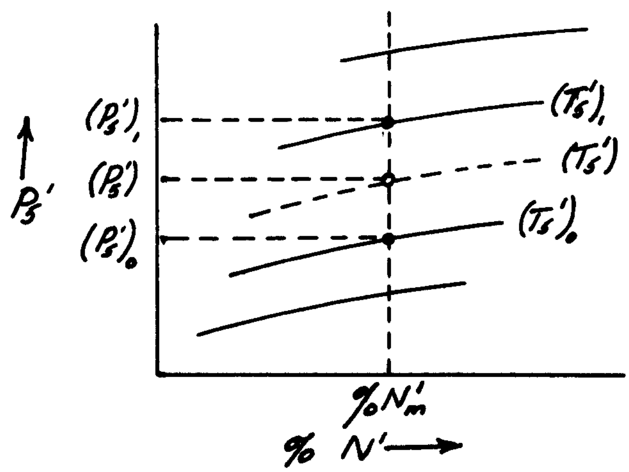


Fig 12
Enlarged Section of P_s' 3-D Plot

In Fig. 12 for a given percent corrected speed $(\% N)_m$ take any two adjacent T_s' lines such that linear changes can be assumed. Then a small change in T_s' results in a corresponding change in P_s' .

Therefore by proportioning:

$$\frac{(T_s') - (T_s')_0}{(T_s')_1 - (T_s')_0} = \frac{(P_s') - (P_s')_0}{(P_s')_1 - (P_s')_0} \tag{4}$$

$$(T_s') - (T_s')_0 = \frac{(T_s')_1 - (T_s')_0}{(P_s')_1 - (P_s')_0} \left[(P_s') - (P_s')_0 \right] \tag{5}$$

Equation (5) can be written in terms of incremental changes.

$$\Delta T_s' = \frac{(\Delta T_s')_{1-0}}{(\Delta P_s')_{1-0}} \Delta P_s' \tag{6}$$

In (6) $\frac{(\Delta T_s')_{1-0}}{(\Delta P_s')_{1-0}}$ is recognized as the slope of the change which varied linearly between the reference condition (0) and the new condition (1). Hence, as the increments get smaller and smaller, in the limit they can be written as differentials,

$$d(T_s') = \frac{\partial (T_s')}{\partial (P_s')} d(P_s') \tag{7}$$

$$\Delta (T_s') = \frac{\partial (T_s')}{\partial (P_s')} \Delta (P_s') \tag{8}$$

Eq. (8) was written where it is understood that for evaluation purposes using numerical data the differentials such as $d(T_s')$ and $d(P_s')$ have finite values and it is convenient to use the incremental form. Comparing Eq. (8) to Eq. (6) it is noted that

$$\frac{\partial (T_s')}{\partial (P_s')} \equiv \frac{\Delta (T_s')_{1-0}}{\Delta (P_s')_{1-0}} = \text{one engine partial} \tag{9}$$

The other two engine partials that are used in this analysis are

$$\frac{\partial(T_5')}{\partial(P_{s3}')} \quad \text{and} \quad \frac{\partial(T_5')}{\partial(N_f')}$$

Referring again to any one of the 3-D plots, it will be noted that the values of the engine partials, as they are calculated from point to point along any constant $(\%N)$ line, will be slightly different, hence the value to be used should be an average of all the determinations. This again can best be accomplished by having the engine manufacturer compute the overall average with the engine simulator.

In all of the succeeding work percent changes will be used, hence it will be helpful to define what is meant by "percent partial" and how the "percent partial" is related to the basic engine partial. Again refer to Eq. (4) and note that this equation can be written without altering its equality by dividing the numerator and denominator of the left side fraction by $(T_5')_0$ and dividing the numerator and denominator of the right side fraction by $(P_5')_0$. For example:

$$\frac{\dfrac{(T_5') - (T_5')_0}{(T_5')_0}}{\dfrac{(T_5')_1 - (T_5')_0}{(T_5')_0}} = \frac{\dfrac{(P_5') - (P_5')_0}{(P_5')_0}}{\dfrac{(P_5')_1 - (P_5')_0}{(P_5')^0}} \tag{10}$$

Multiplying both numerator and denominator of both sides of (10) by 100 changes the expression to percent.

$$\frac{(T_s')-(T_s)_o}{(T_s')_o} \times 100 = \frac{\dfrac{(T_s)_1-(T_s')_o}{(T_s')_o}}{\dfrac{(P_s')_1-(P_s')_o}{(P_s')_o}} \left[\frac{(P_s')-(P_s')_o}{(P_s')_o}\right] \times 100 \tag{11}$$

Eq. (11) is now written in percent incremental form:

$$\%\,\Delta(T_s') = \frac{\%(\Delta T_s')_{1-o}}{\%(\Delta P_s')_{1-o}}\,\%\,\Delta(P_s') \tag{12}$$

where,

$$\%\,\Delta(T_s') = \frac{(T_s)-(T_s')_o}{(T_s)_o'} \times 100 \tag{13}$$

$$\%\,\Delta(P_s') = \frac{(P_s')-(P_s')_o}{(P_s')_o} \times 100 \tag{14}$$

Now let,

$$\delta(T_s')_{1-o} \equiv \%\,\Delta(T_s')_{1-o} = \frac{(T_s')_1-(T_s')_o}{(T_s')_o} \times 100 \tag{15}$$

$$\delta(P_s')_{1-o} \equiv \%\,\Delta(P_s')_{1-o} = \frac{(P_s')_1-(P_s')_o}{(P_s')_o} \times 100 \tag{16}$$

Next, define "percent partial" as the ratio of (15) to (16), or, generalizing by dropping the subscripts,

$$\frac{\delta(T_5')}{\delta(P_5')} = \frac{\dfrac{(T_5')_1-(T_5')_0}{(T_5')_0}\times 100}{\dfrac{(P_5')_1-(P_5')_0}{(P_5')_0}\times 100} \equiv \frac{(P_5')_0}{(T_5')_0}\frac{\Delta(T_5')_{1-0}}{\Delta(P_5')_{1-0}} = \frac{(P_5')_0}{(T_5')_0}\frac{\partial(T_5')}{\partial(P_5')} \qquad (17)$$

where $(P_5')_0$ and $(T_5')_0$ are the reference values of P_5' and T_5' at which $\frac{\partial T_5'}{\partial P_5'}$ was evaluated.

Similarly, the other two "percent partials" that will be used are:

$$\frac{\delta T_5'}{\delta P_{S3}'} = \frac{(P_{S3}')_0}{(T_5')_0}\frac{\partial T_5'}{\partial P_{S3}'} \qquad (18)$$

$$\frac{\delta T_5'}{\delta W_f'} = \frac{(W_f')_0}{(T_5')_0}\frac{\partial T_5'}{\partial W_f'} \qquad (19)$$

Finally, in terms of percent, using "percent partials" the incremental equations for the three deterioration sensitive gas generator parameters that will be used in the logic system are:

$$\boxed{\begin{aligned}
\%\Delta T_5' &= \frac{\delta T_5'}{\delta P_5'}\,\%\Delta P_5' && (20)\\
\%\Delta T_5' &= \frac{\delta T_5'}{\delta P_5'}\,\%\Delta P_{S3}' && (21)\\
\%\Delta T_5' &= \frac{\delta T_5'}{\delta W_f'}\,\%\Delta W_f' && (22)
\end{aligned}}$$

Up to this point it has been shown how the percent partials have been evaluated and how they relate to the basic engine partial. Equations (20), (21) and (22) are general, but when they are used it must be remembered that the value of the percent partial is a function of the operating point. In other words, these percent partials are functions of the percent corrected speed $\%N'$. This fact is readily appreciated by noting the slope changes of the T_5' lines of each of the 3-D curves, Fig. 5, 6 and 7 when $\%N'$ changes. Consequently, it becomes necessary to generate a set of curves, using the simulator, that gives these percent partials as functions of the percent corrected speed $(\%N')$. Fig. 13 is a sketch of what these functions might look like.

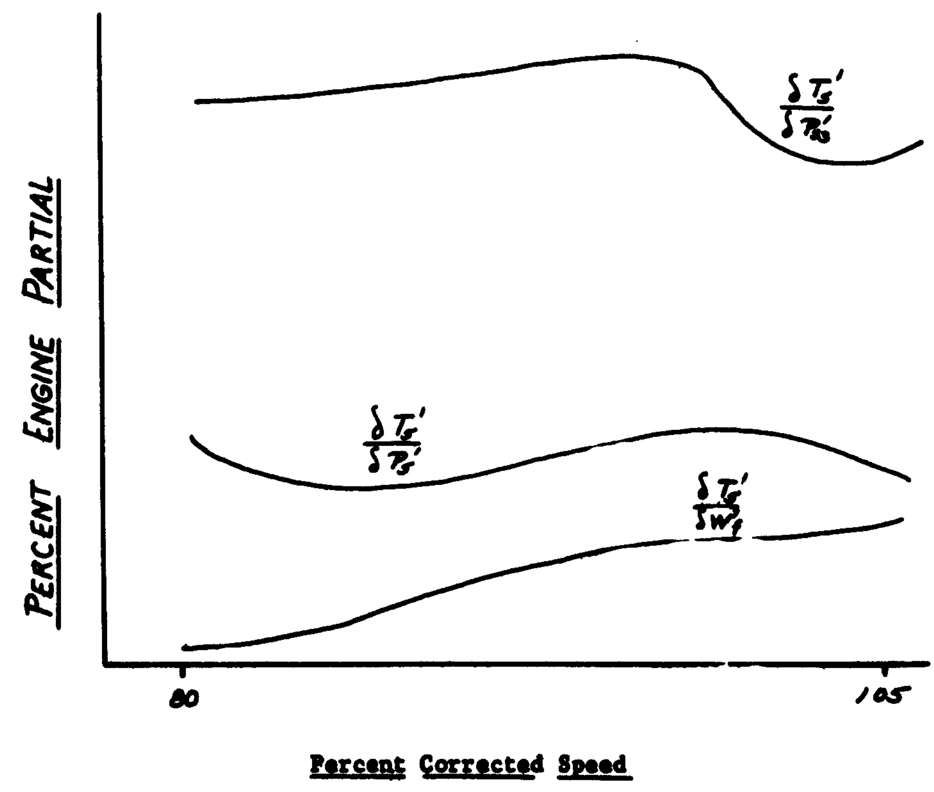


Fig. 13 - Percent Engine Partials vs. $\%N'$

1.3 Deterioration Partials

Use was made of the jet engine simulator to relate the sensitivity of various engine thermodynamic and performance variables to the deterioration of the three basic engine component characteristics. These components are the compressor, the burner and the turbine. Several different deterioration parameters were considered, but the ones finally selected were compressor efficiency function ϕ_c , combustion efficiency η_b , and turbine efficiency η_t . Any change that might occur in component characteristics due to deterioration or any other cause can be considered as an effective change in one of the above. By applying a known change in these deterioration parameters, it was possible to evaluate the resulting changes in the basic gas generator parameters and thus determine what has been named the "deterioration partials." Several operating points were run on the simulator, covering standard, hot and cold days, and the power setting, altitude and mach ranges of the engine. The data then was tabulated similar to that shown in Table 16 for each stable operating point. The partials tabulated are in percent as defined in (17), (18) and (19).

Table 16

Percent Deterioration Partials

Deterioration Mode	$\frac{\delta P_{s3}}{\delta}$	$\frac{\delta W_f}{\delta}$	$\frac{\delta P_t}{\delta}$	$\frac{\delta T_5}{\delta}$	$\frac{\delta F_n}{\delta}$	$\frac{\delta SFC}{\delta}$	$\frac{\delta T_4}{\delta}$	etc.
ϕ_c	a_1	b_1	c_1	d_1	e_1	f_1	g_1	etc.
η_t	a_2	b_2	c_2	d_2	e_2	f_2	g_2	etc.
η_b	a_3	b_3	c_3	d_3	e_3	f_3	g_3	etc.

The compressor function ϕ_c involves the compressor efficiency and the corrected air flow W_a'. A 1% change in ϕ_c is equivalent to a 1% change in η_c plus a 2% change in W_a', i.e.,

$$1\% \Delta \phi_c = 1\% \Delta \eta_c + 2\% \Delta W_a' \tag{23}$$

The numbers $a_1, a_2 \ldots, b_1, b_2 \ldots$ etc. represent the percent change to be expected in the operating value of a dependent variable following a change of 1% in the component characteristic considered as an independent variable. In fact, these numbers are the "percent deterioration partials." In use, for example, suppose c_2 = -1.042, then the percent incremental equation involving can be written:

$$\% \Delta P_5 = \frac{\delta P_5}{\delta \eta_t} \% \Delta \eta_t$$

In this equation $\frac{\delta P_5}{\delta \eta_t} = c_2 = -1.042$

If we assume the turbine efficiency deteriorates 1%, or

$\Delta \eta_t$ = -1.0, then

ΔP_5 = (-1.042) (-1.0) = +1.042

This says that if nothing else deteriorated in the engine a 1.042% increase in the turbine discharge total pressure (P_5) indicates a 1% decrease in the efficiency of the turbine. Hence, from Table 16, using corrected values of the engine parameters, the percent incremental individual deterioration equations can be written:

$$\% \Delta P_{s3}' = \frac{\delta P_{s3}'}{\delta \phi_c} \% \Delta \phi_c \tag{24}$$

$$\% \Delta P_{s3}' = \frac{\delta P_{s3}'}{\delta \eta_t} \% \Delta \eta_t \tag{25}$$

$$\% \Delta P_{s3}' = \frac{\delta P_{s3}'}{\delta \eta_b} \% \Delta \eta_b \tag{26}$$

$$\% \Delta w_f' = \frac{\delta w_f'}{\delta \phi_c} \% \Delta \phi_c \qquad (27)$$

$$\% \Delta w_f' = \frac{\delta w_f'}{\delta \eta_t} \% \Delta \eta_t \qquad (28)$$

$$\% \Delta w_f' = \frac{\delta w_f'}{\delta \eta_b} \% \Delta \eta_b \qquad (29)$$

$$\% \Delta P_5' = \frac{\delta P_5'}{\delta \phi_c} \% \Delta \phi_c \qquad (30)$$

$$\% \Delta P_5' = \frac{\delta P_5'}{\delta \eta_t} \% \Delta \eta_t \qquad (31)$$

$$\% \Delta P_5' = \frac{\delta P_5'}{\delta \eta_b} \% \Delta \eta_b \qquad (32)$$

--- etc ---

It is understood here that the component efficiencies constitute independent variables and the corrected gas generator parameters P_{s3}', W_f' P_5', T_5' etc. are the dependent variables. For small changes in the independent variables, the component characteristic effects may be considered cumulative and the net effect of compound changes (i.e., more than one deterioration occurring simultaneously) can be estimated by linearly summing the effects of each individual change. Therefore, adding (24), (25) and (26); (27), (28) and (29); (30), (31) and (32); etc. the total effective percent changes become:

$$\% \Delta P_{s3}' = a_1 \% \Delta \phi_c + a_2 \% \Delta \eta_t + a_3 \% \Delta \eta_b \tag{33}$$

$$\% \Delta W_f' = b_1 \% \Delta \phi_c + b_2 \% \Delta \eta_t + b_3 \% \Delta \eta_b \tag{34}$$

$$\% \Delta P_5' = c_1 \% \Delta \phi_c + c_2 \% \Delta \eta_t + c_3 \% \Delta \eta_b \tag{35}$$

$$\% \Delta T_5' = d_1 \% \Delta \phi_c + d_2 \% \Delta \eta_t + c_3 \% \Delta \eta_b \tag{36}$$

$$--- \ etc \ ---$$

where the percent "deterioration partials" are:

$$\left.\begin{array}{lll} a_1 = \dfrac{\delta P_{s3}'}{\delta \phi_c}, & a_2 = \dfrac{\delta P_{s3}'}{\delta \eta_t}, & a_3 = \dfrac{\delta P_{s3}'}{\delta \eta_b} \\ b_1 = \dfrac{\delta W_f'}{\delta \phi_c}, & b_2 = \dfrac{\delta W_f'}{\delta \eta_t}, & b_3 = \dfrac{\delta W_f'}{\delta \eta_b} \\ & ---- \ etc \ ---- & \end{array}\right\} \tag{37}$$

The values of the "percent deterioration partials" (37) are functions of the stabilized operation points. Consequently, data for each point in the form of Table 16 must be supplied by the engine manufacturer for use in building up the logic system. For any given engine model this needs to be done only once. For computer memory storage of this kind of data these "percent deterioration partials" should be defined by analytical expressions relating them to the flight condition, that is, P_2 , T_2 and $\% N'$. Functionally written:

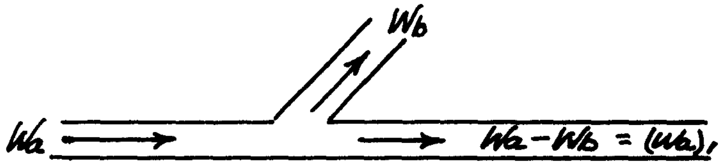
$$\left.\begin{array}{ll} a_1 = f_1(P_2, T_2, \% N'), & a_2 = f_2(P_2, T_2, \% N') \\ b_1 = f_3(P_2, T_2, \% N), & b_2 = f_4(P_2, T_2, \% N') \\ & --- \ etc \ --- \end{array}\right\} \tag{38}$$

1.4 Parameter Corrections For Bleed Air Extraction

If bleed air extraction significantly affects the magnitudes of the gas generator parameters, then the measured values of these parameters must be corrected before they are used in the analytical procedures to determine deterioration. To make these corrections it is necessary to know the magnitude of the bleed effect and the bleed partial for the flight operation point under consideration. The percent bleed air is inferred from either a pressure measurement or airframe manufacturer supplied data, and the corresponding partial can be derived from the tab-bulletin of performance of the engine.

The following discussion illustrates the bleed correction procedure to be used.

Consider the simple air flow diagram pictured below:



where :

W_a = compressor inlet air flow - lbs/sec

W_b = bleed air lbs/sec

$(W_a)_1$ = airflow available for engine use

Now the percent change in total airflow $\%(W_a)$ can be written:

$$\% \Delta W_a = \frac{(W_a) - (W_a)_1}{(W_a)} \times 100 = \frac{W_b}{W_a} \times 100 \qquad (39)$$

Any one of the gas generator parameters, for example T_6', can be expressed as a percentage change of W_a

$$\% \Delta T_6' = \frac{\delta T_6'}{\delta W_a} \% \Delta W_a \qquad (40)$$

Where it is understood as defined in (15) and (16) that

$$\delta T_6' = \%\Delta(T_6')_{1-0} = \frac{(T_6')_1-(T_6')_0}{(T_6')_0} \times 100$$

$$\delta W_a = \%\Delta(W_a)_{1-0} = \frac{(W_a)_1-(W_a)_0}{(W_a)_0} \times 100$$

But from (39), (40) can be written

$$\% \Delta T_6' = \frac{\delta T_6'}{\delta(W_b/W_a)} \% \left(\frac{W_b}{W_a}\right) \tag{41}$$

Similarly, the other engine parameter percent changes become:

$$\% \Delta W_f' = \frac{\delta W_f'}{\delta(W_b/W_a)} \% \left(\frac{W_b}{W_a}\right) \tag{42}$$

$$\% \Delta P_5' = \frac{\delta P_5'}{\delta(W_b/W_a)} \% \left(\frac{W_b}{W_a}\right) \tag{43}$$

$$\% \Delta P_{s3}' = \frac{\delta P_{s3}'}{\delta\left(\frac{W_b}{W_a}\right)} \% \left(\frac{W_b}{W_a}\right) \tag{44}$$

It will be recognized that $\frac{\delta T_6'}{\delta\left(\frac{W_b}{W_a}\right)}$, $\frac{\delta W_f'}{\delta\left(\frac{W_b}{W_a}\right)}$, etc., are the "percent bleed partials."

The correction equations will now be derived. Continuing with the example of T_6', let

$(T_6')_m$ = the measured value of T_6' with bleed

$(T_6')_0$ = the measured value of T_6', no bleed

Then

$$\% \Delta (T_5')_m = \frac{\delta T_5'}{\delta\left(\frac{W_b}{W_a}\right)} \% \frac{W_b}{W_a} = \frac{(T_5')_m - (T_5')_o}{(T_5')_o} \times 100$$

Solving for $(T_5')_o$ and recognizing that it is actually the value of T_5' that would have existed if there were no bleed, and therefore becomes the corrected value of T_5', i.e., $(T_5')_o \equiv (T_5')$ corr.:

$$(T_5')_{corr} = \frac{(T_5')_m}{\frac{\delta T_5'}{\delta\left(\frac{W_b}{W_a}\right)}\left(\frac{W_b}{W_a}\right) + 1} \tag{45}$$

Similarly

$$(W_f')_{corr} = \frac{(W_f')_{meas.}}{\frac{\delta(W_f')}{\delta\left(\frac{W_b}{W_a}\right)}\left(\frac{W_b}{W_a}\right)_m + 1} \tag{46}$$

$$(P_5')_{corr} = \frac{(P_5')_m}{\frac{\delta(P_5')}{\delta\left(\frac{W_b}{W_a}\right)}\left(\frac{W_b}{W_a}\right)_m + 1} \tag{47}$$

$$(P_{s5}')_{corr} = \frac{(P_{s5}')_m}{\frac{\delta(P_{s5}')}{\delta\left(\frac{W_b}{W_a}\right)}\left(\frac{W_b}{W_a}\right)_m + 1} \tag{48}$$

Therefore, when bleed extraction is present, before the gas generator parameters can be used in the 3-D and 2-D curves of Figs. 5, 6, 7, 9, 10 and 11 respectively, they must be corrected in accordance with Eqs. (45),(46), (47) and (48).

1.5 The Logic System

The subject matter described in the previous sections 1.1 through 1.4 is important background material that is necessary not only for the understanding but also for the construction of the logic systems described in this section. A generalized logic system will be described first, and then two derived simplified systems will be discussed.

a) A generalized logic system for engine performance in flight is inherent in the relationships defined by Equations (33), (34), (35) and (36) of section 1.3. However, since there are four equations and only three unknowns, these equations cannot be solved simultaneously for $\Delta\phi_c$, $\Delta\eta_t$ and $\Delta\eta_b$ in terms of the dependent variables $\%\Delta P_{t3}$, $\%\Delta w_f$, $\%\Delta P_5$ and $\%\Delta T_5$ This situation can be resolved in one of two ways. An additional deterioration mode can be added to each of the four equations to satisfy the conditions of four equations in four unknowns. Such a mode could be percent change in the turbine inlet cross section ($\%\Delta A_4$), the percent change in the pressure ratio across the burner ($\%\Delta \frac{P_4}{P_3}$), or any other deterioration mode that may be significant. A second and perhaps better way to relate the three independent, unknown deterioration parameters, $\%\Delta\phi_c$, $\%\Delta\eta_t$ and $\%\Delta\eta_b$ respectively, to the difference in a measured and predicted value of corrected EGT expressed

as a percent of a reference value of T_5'. If deterioration changes are assumed to be small, then linear relationships can be set up using what we have chosen to call "percent system sensitivity partials". These partials will be derived subsequently.

In this system use is made of the 3-D plots, Figs. 5,6 and 7 where the corrected gas generator parameters, P_{s3}', P_5' and W_f' are plotted against percent corrected speed ($\% N'$) for lines of constant T_5'. These plots are entered with measured values of P_{s3}', W_f' and P_5' for a given $\% N'$ to determine predicted values of T_5'. The predicted values of T_5' are then compared to the measured T_5', and the results expressed in percent. Equations (1), (2) and (3) define these percentages. For convenience they are repeated here:

$$\alpha = \left[\frac{(T_5')_p - (T_5')_m}{(T_5')_{Ref}}\right]_{P_5'} \times 100 \tag{1}$$

$$\beta = \left[\frac{(T_5')_p - (T_5')_m}{(T_5')_{Ref}}\right]_{W_f'} \times 100 \tag{2}$$

$$\gamma = \left[\frac{(T_5')_p - (T_5')_m}{(T_5')_{Ref}}\right]_{P_{s3}'} \times 100 \tag{3}$$

Similarly, as was done with the percent deterioration partials displayed in Table 16, the "percent system sensitivity partials" can be tabulated against the deterioration mode as shown in Table 17.

Table 17

Percent System Sensitivity Partials

Deterioration Mode	α	β	γ
$\% \Delta \phi_c$	A_1	B_1	C_1
$\% \Delta \eta_t$	A_2	B_2	C_2
$\% \Delta \eta_b$	A_3	B_3	C_3

From Table 17 the individual percent incremental equations can be written as follows:

$$\alpha_1 = A_1 \% \Delta \phi_c \quad (49)$$

$$\alpha_2 = A_2 \% \Delta \eta_t \quad (50)$$

$$\alpha_3 = A_3 \% \Delta \eta_b \quad (51)$$

$$\beta_1 = B_1 \% \Delta \phi_c \quad (52)$$

$$\beta_2 = B_2 \% \Delta \eta_t \quad (53)$$

$$\beta_3 = B_3 \% \Delta \eta_b \quad (54)$$

$$\gamma_1 = C_1 \% \Delta \phi_c \quad (55)$$

$$\gamma_2 = C_2 \% \Delta \eta_t \quad (56)$$

$$\gamma_3 = C_3 \% \Delta \eta_b \quad (57)$$

Here the "percent system sensitivity partials" are:

$$A_1 = \left[\frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \Phi_c} - \frac{\delta T_s'}{\delta \Phi_c} \right]_{P_s'} \tag{58}$$

$$A_2 = \left[\frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \eta_t} - \frac{\delta T_s'}{\delta \eta_t} \right]_{P_s'} \tag{59}$$

$$A_3 = \left[\frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \eta_b} - \frac{\delta T_s'}{\delta \eta_b} \right]_{P_s'} \tag{60}$$

$$B_1 = \left[\frac{\delta T_s'}{\delta W_f'} \cdot \frac{\delta W_f'}{\delta \Phi_c} - \frac{\delta T_s'}{\delta \Phi_c} \right]_{W_f'} \tag{61}$$

$$B_2 = \left[\frac{\delta T_s'}{\delta W_f'} \cdot \frac{\delta W_f'}{\delta \eta_t} - \frac{\delta T_s'}{\delta \eta_t} \right]_{W_f'} \tag{62}$$

$$B_3 = \left[\frac{\delta T_s'}{\delta W_f'} \cdot \frac{\delta W_f'}{\delta \eta_b} - \frac{\delta T_s'}{\delta \eta_b} \right]_{W_f'} \tag{63}$$

$$C_1 = \left[\frac{\delta T_s'}{\delta P_{s3}'} \cdot \frac{\delta P_{s3}'}{\delta \Phi_c} - \frac{\delta T_s'}{\delta \Phi_c} \right]_{P_{s3}'} \tag{64}$$

$$C_2 = \left[\frac{\delta T_s'}{\delta P_{s3}'} \cdot \frac{\delta P_{s3}'}{\delta \eta_t} - \frac{\delta T_s'}{\delta \eta_t} \right]_{P_{s3}'} \tag{65}$$

$$C_3 = \left[\frac{\delta T_s'}{\delta P_{s3}} \cdot \frac{\delta P_{s3}}{\delta \eta_b} - \frac{\delta T_s'}{\delta \eta_b} \right]_{P_{s3}'} \tag{66}$$

It will be noted that these partials are functions of both engine and deterioration partials which were discussed in sections 1.2 and 1.3 respectively.

A simple derivation will now be performed to demonstrate where the "percent system sensitivity partials" come from. For example, consider the partial represented by A_2 in Equation (59). Referring to the 3-D plot of P_s' (Fig. 6), let $(P_s')_m$ be the measured value of P_s' resulting from a deterioration taking place in the engine. Then for the given measured value of corrected speed $(\% N')_m$ at which P_s' was measured, the percent change in P_s' can be written:

$$(\% \Delta P_s')_m = \frac{(P_s')_m - (P_s')_{Ref}}{(P_s')_{Ref}} \times 100 \qquad (67)$$

Now for illustrative purposes only let it be assumed that the deterioration which caused P_s' to change was due solely to a decrease in the turbine efficiency. Thus from Eq. (5.1-31) the measured value of P_s' also can be expressed in terms of the turbine deterioration partial, i.e.,

$$(\% \Delta P_s')_m = \frac{\delta P_s'}{\delta \eta_t} \% \Delta \eta_t \qquad (31)$$

Since (31) and (67) are equivalent,

$$(\% \Delta P_s')_m = \frac{(P_s')_m - (P_s')_{Ref}}{(P_s')_{Ref}} = \frac{\delta P_s'}{\delta \eta_t} \% \Delta \eta_t \qquad (68)$$

In a similar fashion the percent change in the measured value of T_s', resulting from the same deterioration, can be written:

$$\boxed{(\% \Delta T_s')_m = \left[\frac{(T_s')_m - (T_s')_{Ref}}{(T_s')_{Ref}}\right]_{P_s} \times 100 = \frac{\delta T_s'}{\delta \eta_t} \% \Delta \eta_t} \quad (69)$$

Now from the 3-D plot (Fig. 6), $(P_s')_m$ also determines a predicted value of T_s'. This is expressed in a percent change from reference as:

$$(\% \Delta T_s')_p = \left[\frac{(T_s')_p - (T_s')_{Ref}}{(T_s')_{Ref}}\right]_{P_s'} \times 100 \quad (70)$$

But this percent change can also be expressed, using the percent engine partials, as shown in Eq. (20), i.e.,

$$(\% \Delta T_s')_p = \frac{\delta T_s'}{\delta P_s'} (\% \Delta P_s')_m \quad (20)$$

Therefore, since (20) and (70) are equivalent,

$$(\% \Delta T_s')_p = \left[\frac{(T_s')_p - (T_s')_{Ref}}{(T_s')_{Ref}}\right]_{P_s'} \times 100 = \frac{\delta T_s'}{\delta P_s'} (\% \Delta P_s')_m \quad (71)$$

Using only that portion of (68) containing the partial, substitute (68) into (71) to eliminate $(\Delta P_s')_m$ and obtain:

$$\boxed{(\% \Delta T_s')_p = \left[\frac{(T_s')_p - (T_s')_{Ref}}{(T_s')_{Ref}}\right]_{P_s'} \times 100 = \frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \eta_t} \% \Delta \eta_t} \quad (72)$$

Finally, subtract (69) from (72). Firstly, note that

$$\left[(\%\Delta T_s')_p - (\%\Delta T_s')_m\right]_{P_s'} = \left[\frac{(T_s')_p - (T_s')_{Ref}}{(T_s')_{Ref}}\right]_{P_s'} \times 100 - \left[\frac{(T_s')_m - (T_s')_{Ref}}{(T_s')_{Ref}}\right]_{P_s'} \times 100$$

$$= \frac{100}{(T_s')_{Ref}}\left[(T_s')_p - (T_s')_{Ref} - (T_s')_m + (T_s')_{Ref}\right]_{P_s'}$$

$$= \left[\frac{(T_s')_p - (T_s')_m}{(T_s')_{Ref}}\right]_{P_s'} \times 100 \qquad (73)$$

And secondly, that also

$$\left[(\%\Delta T_s')_p - (\%\Delta T_s')_m\right]_{P_s'} = \frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \eta_t} \%\Delta \eta_t - \frac{\delta T_s'}{\delta \eta_t} \%\Delta \eta_t \qquad (74)$$

Therefore, since (71) and (72) are equivalent expressions:

$$\boxed{\left[\frac{(T_s')_p - (T_s')_m}{(T_s')_{Ref}}\right]_{P_s'} \times 100 = \left[\frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \eta_t} - \frac{\delta T_s'}{\delta \eta_t}\right]_{P_s'} \%\Delta \eta_t}$$

(75)

If we let

$$A_2 = \left[\frac{\delta T_s'}{\delta P_s'} \cdot \frac{\delta P_s'}{\delta \eta_t} - \frac{\delta T_s'}{\delta \eta_t}\right]$$ - the "percent

system sensitivity partial," and

$$\alpha_2 = \left[\frac{(T_s')_p - (T_s')_m}{(T_s')_{Ref}}\right]_{P_s'} \times 100 \quad \text{or} \quad \left[(\%\Delta T_s')_p - (\%\Delta T_s')_m\right]_{P_s'}$$

then Eq (75) can be written:

$$\boxed{\alpha_2 = A_2 \% \Delta \eta_t}$$ (See Eq. 50)

The subscripts at the ends of the bracket terms in (75) identify the expression with the corresponding gas generator 3-D plot for P'_{f} .

Refer again to Table 17. For small changes in the independent variables (i.e., $\%\Delta\phi_c$, $\%\Delta\eta_t$ and $\%\Delta\eta_b$) if several deteriorations occur simultaneously, the net effect of compound changes can be estimated by linearly summing the effects of each individual change. Therefore, adding (49), (50) and (51); (52), (53) and (54); (55), (56) and (57), the total effective percent changes become:

$$\alpha = A_1\%\Delta\phi_c + A_2\%\Delta\eta_t + A_3\%\Delta\eta_b. \tag{76}$$

$$\beta = B_1\%\Delta\phi_c + B_2\%\Delta\eta_t + B_3\%\Delta\eta_b \tag{77}$$

$$\gamma = C_1\%\Delta\phi_c + C_2\%\Delta\eta_t + C_3\%\Delta\eta_b \tag{78}$$

Equations (76), (77) and (78) yield the following general solutions for $\%\Delta\phi_c$, $\%\Delta\eta_t$ and $\%\Delta\eta_b$ respectively:

$$\%\Delta\phi_c = \frac{(B_2C_3 - B_3C_2)\alpha + (A_3C_2 - A_2C_3)\beta + (A_2B_3 - A_3B_2)\gamma}{D}. \tag{79}$$

$$\%\Delta\eta_t = \frac{(B_3C_1 - B_1C_3)\alpha + (A_1C_3 - A_3C_1)\beta + (A_3B_1 - B_3A_1)\gamma}{D} \tag{80}$$

$$\%\Delta\eta_b = \frac{(B_1C_2 - B_2C_1)\alpha + (A_2C_1 - A_1C_2)\beta + (A_1B_2 - A_2B_1)\gamma}{D}. \tag{81}$$

where

$$D = A_1(B_2C_3 - B_3C_2) + A_2(B_3C_1 - B_1C_3) + A_3(B_1C_2 - B_2C_1) \tag{82}$$

Equations (76), (77) and (78) constitute the generalized logic system for the single spool engine. The component deterioration effects can now be isolated by the solution of these equations. The measured EGT's are defined by Eqs. (1), (2) and (3) for α, β and γ corresponding to the measured gas generator parameters, $(P_3')_m$, $(W_f')_m$ and $(P_{3s}')_m$, respectively, and the "percent system sensitivity partials" A_1, A_2, A_3, B_1, etc., by Eqs. (58) through (66). Since these partials are functions of the stabilized operation points in space, enough data must be provided by the engine manufacturer to obtain values of these partials applicable to the test conditions at which the measured data is acquired. For computer memory storage, this kind of data, if possible, is best represented as being functionally related to the flight condition, that is, to P_2, T_2 and $\%N$. For example:

$$\left.\begin{array}{l} A_1 = F_1(P_2, T_2, \%N')\,;\; A_2 = F_2(P_2, T_2, \%N')\,; \\ B_1 = F_3(P_2, T_2, \%N')\,;\; B_2 = F_4(P_2, T_2, \%N')\,; \\ \quad --- \text{ etc } --- \end{array}\right\} \qquad (83)$$

Again this type of data needs to be generated only once for a given type of engine.

The computed percent deterioration changes (79), (80) and (81) are then subjected to a data smoothing treatment (See Section 2.5) to damp out random fluctuations, and the smoothed data is then plotted against engine operating time and compared to limits. The criteria and calculation of the limiting conditions are discussed in Section 1.6.

b) A simplified flight performance logic system is obtained when several of the "percent system sensitivity partials" of Table 17 are zero. An analysis of the G.E.-J79-5A engine revealed that over the flight operating range of the engine four of these partials were zero or nearly zero for practical purposes. Specifically, for the J79-5A engine:

$$A_3 = B_2 = C_2 = C_3 = 0 \tag{84}$$

For this condition Table 17 is simplified to that shown in Table 18.

Table 18

Percent System Sensitivity Partials

G.E.-J79-5A&B Engine

Deterioration Mode	α	β	γ
$\% \Delta \phi_c$	A_1	B_1	C_1
$\% \Delta \eta_t$	A_2	0	0
$\% \Delta \eta_b$	0	B_3	0

Also, Eqs. (79), (80) and (81) reduce to the following:

$$\% \Delta \phi_c = \frac{\gamma}{C_1} \tag{85}$$

$$\% \Delta \eta_t = \frac{C_1 \alpha - A_1 \gamma}{A_2 C_1} \tag{86}$$

$$\% \Delta \eta_b = \frac{C_1 \beta - B_1 \gamma}{B_3 C_1} \tag{87}$$

All of the statements pertaining to the generalized logic system described in the preceding section 1.5 (a) apply here. That is, the 3-D plots of Figs. 5, 6 and 7 must be used; the system partials are functions of the flight conditions, etc. However, some simplification in the computation may be achieved by solving the equations dictated by Table 18 in terms of the alphas (α), betas (β) and gammas (γ), (the temperature functions) rather than the deterioration parameters as done in (85), (86) and (87). This is possible because the pattern of the zeros in Table 18 permit a unique isolation of the compressor, turbine and burner degradations without having to solve for these degradations, per se. The following analysis will clarify the concept.

From Table 18 these equations can be written (See Eqs. 49 to 57):

$$\alpha = \alpha_1 + \alpha_2 \equiv A_1 \% \Delta\phi_c + A_2 \% \Delta\eta_t \tag{88}$$

$$\beta = \beta_1 + \beta_3 \equiv \beta_1 \% \Delta\phi_c + \beta_3 \% \Delta\eta_b \tag{89}$$

$$\boxed{\gamma = \gamma_1 = C_1 \% \Delta\phi_c} \quad \text{Compressor} \tag{90}$$

Since a change in γ is solely caused by a change in the compressor, Eq. (90) uniquely isolates the compressor degradation. Therefore, the change in α in (88) caused by the turbine deterioration alone is as follows: From (88)

$$\alpha_2 = \alpha - \alpha_1 \tag{91}$$

But from (49) and (90)

$$\% \Delta\phi_c = \frac{\alpha_1}{A_1} \equiv \frac{\gamma_1}{C_1} \equiv \frac{\gamma}{C_1}$$

therefore

$$\alpha_1 = \frac{A_1 \gamma}{C_1} \tag{92}$$

Substitute (92) into (91)

$$\boxed{\alpha_2 = \alpha - \frac{A_1 \gamma}{C_1}} \quad \textit{Turbine} \tag{93}$$

Proceeding in a similar manner, the change in β in (89) caused by the burner deterioration alone is as follows. From (89)

$$\beta_3 = \beta - \beta_1 \tag{94}$$

But from (52) and (90)

$$\% \Delta \phi_c = \frac{\beta_1}{\beta} \equiv \frac{\gamma_1}{C_1} \equiv \frac{\gamma}{C_1}$$

Therefore

$$\beta_1 = \frac{B_1 \gamma}{C_1} \tag{95}$$

Substitute (95) into (94)

$$\boxed{\beta_3 = \beta - \frac{B_1 \gamma}{C_1}} \quad \textit{Burner} \tag{96}$$

Again, the data calculated by either Eqs. (85), (86) and (87) or Eqs (90), (93) and (96) are smoothed, plotted against operating time and compared to limits.

c) When an engine is tested on the ground, the set of 3-D plots used in the flight test operation, reduces to 2-D plots, similar to those shown in Figs. 9, 10, and 11. Also, since the tests can now be performed at one corrected speed (i.e., $\%N' = 90\%$), several other simplications can be made, such as; a simple curve of T_2 vs. $\%N'$ is needed to set the physical speed to give $\%N' = 90\%$ (See Fig. 8); only one set of engine partials corresponding to $\%N' = 90\%$ is required; and the percent deterioration and/or percent system sensitivity partials are provided as functions of only T_2 at $\%N' = 90\%$. The generalized analysis described in 1.5 (a) is applicable and for a G.E.-J79-5A engine Eqs. (85), (86) and (87) or Eqs. (90), (93), and (96) are valid.

In general for the analyses described in 1.5 (a) and (b), bleed corrections must be applied to the measured gas generator parameters. These corrections are explained in Section 1.4 of this Appendix. For the ground test it is assumed that bleed air is shut off before test data is taken.

1.6 <u>Limit Determination</u>

a) <u>Criteria:</u> The limit of changes permissible is derived from the effect of the deterioration on engine performance. The criteria established for the initial limit specifications are whichever occurs first of:

1. **A decrease of 10% in net thrust**

2. **An increase of 10% in specific fuel consumption**

3. **An increase of 4 times in the consumption of hot section parts life. In the G.E.-J79-5A&B engine this is equivalent to an increase of 45°R in T_4 (turbine inlet temperature) applicable only in the constant EGT mode of operation.**

4. **Any mechanical or operational difficulty produced by the deterioration. Compressor stall is the limiting factor on compressor deterioration. This is comparable to a -1 to -2% change in ϕ_c on the J79-5A&B engine.**

b) <u>Calculation of Limits on the Deterioration Parameters</u>

The following is the analysis procedure that was used to obtain numerical evaluations of the limits on the deterioration parameters ϕ_c , η_t and η_b as dictated by the previously itemized criteria. In the following discussion illustrative numbers will be used to help clarify the procedural method.

The criteria give specific values to certain parameters that represent the changes allowed. These are:

$$\% \Delta F_n = -10\% \tag{97}$$

$$\% \Delta SFC = +10\% \tag{98}$$

$$\Delta T_4 = +45^\circ R \tag{99}$$

$$\% \Delta \phi_c = -2\% \tag{100}$$

Each of these criteria are to be applied against the deterioration parameters, ϕ_c , η_t and η_b to see which of the three gas generator parameters F_n , SFC or T_4 are limiting in each case.

Calculation of Limit on ϕ_c - It seems logical that the stall limitation should be the only limit on but this needs to be proven by examining F_n , SFC and T_4 to see if the above criteria for these parameters might not be more limiting than the stall criterion.

For F_n : From the tables of deterioration partials (Refer to Table 16 for example) available for several flight conditions within the operable flight map of the engine, select the percent net thrust deterioration partial that gives the maximum sensitivity, or is numerically the largest. Suppose this partial is

$$\frac{\delta F_n}{\delta \phi_c} = +2$$

Then for small changes

$$\% \Delta F_n = \frac{\delta F_n}{\delta \phi_c} \% \Delta \phi_c$$

Solve for $\% \Delta \phi_c$

$$\% \Delta \phi_c = \frac{\% \Delta F_n}{\delta F_n / \delta \phi_c}$$

But $\% \Delta F_n = -10\%$ from (97)

$$\% \Delta \phi_c = \frac{-10\%}{+2\%} = -5\%$$

For this situation it is concluded that thrust loss is not limiting on ϕ_c since the deterioration function ($\% \Delta \phi_c$) can vary by a minimum of -5% to give a 10% loss in F_n, while -1% or -2% changes in ϕ_c will give stall problems.

<u>For T_4</u>: Since the T_4 applies only in the military and reheat operations of the J79-5A&B, only those tables of deterioration partials for this region of operation are applicable. In addition, since the criterion imposes a constant incremental rise in T_4, it is no longer valid to select the maximum value of the deterioration partial. At any given flight condition both the partial and the reference value of T_4 must be examined together to arrive at the minimum value of $\Delta \phi_c$ For example,

$$\% \Delta T_4 = \frac{\Delta T_4}{(T_4)_{Ref}} \times 100 = \frac{\delta T_4}{\delta \phi_c} \% \Delta \phi_c$$

Solving for $\% \Delta \phi_c$

$$\% \Delta \phi_c = \frac{\Delta T_4 \times 100}{(T_4)_{Ref} \, \delta T_4 / \delta \phi_c}$$

From this relationship it is seen that the product of

$$(T_4)_{Ref} \times \frac{\delta T_4}{\delta \phi_c}$$

must be a maximum to give a minimum $\% \Delta \phi_c$. Suppose this minimum $\% \Delta \phi_c$ is achieved when

$$(T_4)_{Ref} = 1900^\circ R$$

$$\frac{\delta T_4}{\delta \phi_c} = -0.5$$

and from (5.1-99) $\Delta T_4 = 45^\circ R$, then

$$\% \Delta \phi_c = \frac{45 \times 100}{1900 \times (-0.5)} = 4.74\%$$

It is likewise concluded for this example that T_4 is not limiting on ϕ_c since the deterioration function ($\% \Delta \phi_c$) can vary by a minimum of -4.74% to give a +45°R rise in T_4, while -1% or -2% changes in ϕ_c will give stall problems.

<u>For SFC</u>: An analysis similar to that described for F_n is applicable here, It is likewise found that sfc is not limiting on ϕ_c.

In calculating the limits on η_t and η_b analyses similar to that described for ϕ_c were used.

The results of this kind of reasoning provided the following limits on ϕ_c , η_t and η_b :

1. Stall is limiting on ϕ_c , i.e.,

$$\boxed{\% \Delta \phi_c \,(limit) = -2\%} \tag{100}$$

2. sfc limits the turbine efficiency, η_t.

$$\boxed{\% \Delta \eta_t \,(limit) = -5.08\%} \tag{101}$$

This says that for a 10% increase in sfc the turbine must degrade about 5%.

3. sfc limits the burner efficiency, η_b

$$\boxed{\% \Delta \eta_b \,(limit) = -10\%} \tag{102}$$

This says that for a 10% increase in sfc the burner efficiency must degrade 10%.

c) <u>Calculation of Limits on the T_5' Parameter Functions for J79-5A&B Engine</u>

The T_5' parameter functions have been previously defined as the alphas (α), betas (β), and gammas (γ). See Eqs. (1), (2), (3) and (49) through (57). In applying the limits calculated above to α, β and γ , Eqs. (88), (89) and (90) are helpful.

1. For the compressor from Eq. (90) the limit is

$$(\gamma)_{lim} = (\gamma_1)_{lim} = C_1 (\% \Delta \phi_c)_{lim} \tag{103}$$

From (100) for $(\% \Delta \phi_c)_{lim} = -2\%$

$$\boxed{(\gamma_1)_{lim} = -2.0 C_1} \tag{104}$$

If $C_1 \approx -5.3$ $\quad (\gamma_1)_{lim} = +10.6\%$

2. For the turbine from Eq. (88) the limit is

$$(\alpha_2)_{lim} = A_2 (\% \Delta \eta_t)_{lim} \tag{105}$$

From (101) for $(\% \Delta \eta_t)_{lim} = -5.08\%$

$$\boxed{(\alpha_2)_{lim} = -5.08 A_2} \tag{106}$$

If $A_2 \approx -1.4$ $\quad (\alpha_2)_{lim} = +7.20\%$

3. For the burner from Eq. (89) the limit is

$$(\beta_3)_{lim} = B_3 (\% \Delta \eta_b)_{lim} \tag{107}$$

From (102) for $(\% \Delta \eta_b)_{lim} = -10\%$

$$\boxed{(\beta_3)_{lim} = -10 B_3.} \tag{108}$$ *
*

If $B_3 \approx 0.56$; $(\beta_3)_{lim} = -5.6\%$

*
* NOTE: Equations (109) thru (111) are omitted, however, no equations are missing.

5.1.7 <u>Analysis Procedure Summary</u>

The following is a general summary of the steps necessary in the deterioration analysis of the single spool engine having variable exit geometry for airborne data acquisition only.

a) Initially there will be available generic data on the engine model. This will consist of:

1. Three - dimensional plots (3) each of the performance of an undeteriorated engine similar to the plots of Figs. 5,6, and 7.

2. A set of tabulations of the "percent system sensitivity partials" for the three deterioration modes, $\%\Delta\phi_c$ $\%\Delta\eta_b$ and $\%\Delta\eta_b$ similar to the general tabulation shown in Table 18. This kind of data may exist either in tabular form for several selected flight environments, or functions may be generated relating the "percent system sensitivity partials" to P_2, T_2 and $\%N'$.

b) Obtain data at stabilized flight conditions. Automatically acquire 25 sets of data about every 2 hours or once a flight, whichever is shorter. A set of data consists of the parameters listed in Table 14. The 25 sets of data are obtained in rapid sequence.

c) Average the 25 values of each measurement. This calculation is performed in a ground based computer.

d) Correct the average value of the measurement to standard ambient conditions. Corrected parameter expressions are those listed in 1.1. Apply an averaged bleed air correction to these standardized parameters as given in 1.4.

e) Relate the data to the engine degradation functions. This involves the use of the 3-D plots of Figs. 5, 6, and 7 to obtain the alphas (α), betas (β) and gammas (γ) of Eqs. (1), (2) and (3). Substitute these values of α, β and γ either into the general deterioration equations (Eqs. 79, 80, and 81) or the simpler set for the J79 (Eqs. 90, 93 and 96) to obtain the isolated component deterioration parameters. These calculations to be done in a ground based computer.

f) Calculate the log average of the deterioration parameters obtained in step (e). Use the smoothing equation defined in Section 2.5.

g) Plot the log average of deterioration for each component vs. time and compare to limits.

2 Twin Spool Engine Performance Analysis

The twin spool engine analysis method uses a comparison of predicted and measured gas generator characteristics to indicate a change in the engine performance. Theoretically, the same analysis procedure can be used on the twin spool engines as described for the single spool engine, however, more measurements of interstage pressures and temperatures are required to provide a solution of the matrix. This is because the interactions between the two rotor systems prevent knowledge of the entrance conditions to the down stream elements which is necessary to determine the operating condition. Provision for these interstage measurements is not generally available on production engines, and in the opinion of Pratt & Whitney, manufacturers of the twin spool engines, the complexity of these interactions make the EGT comparison method of analysis impractical to apply to twin spool engines.

The analysis method proposed for the twin spool engines, is based on the approach described in Pratt & Whitney Gas Turbine Information Letter No. 15. In this procedure, "predicted" values of engine rotor speeds, fuel flow, exhaust gas temperature and compressor pressure ratio are compared to measured values of these parameters. The predicted values of the parameters are based on the performance of an "average" engine. The difference between the measured and predicted value is an index of the deviation of a specific engine from the average engine. This difference unless it is large is generally not significant since variations in components and adjustments cause engine to engine differences.

Changes in these differences of measured and predicted values are indicative of changes in the thermodynamic performance of the engine and are used as a measure of engine deterioration.

Isolation of the deterioration is obtained through recognition of the pattern of the changes in the parameters. Table 19 below lists approximate changes in some of these parameters for some deteriorations.

Table 19
Gas Generator Characteristics
- Deterioration Changes

Deterioration	Parameter Changes			
	EGT DegF	N_1 rpm	N_2 rpm	FFR lb/hr
100% 1st Stage Turb. Seal Erosion	+27	-100	-270	+200
One Inter. Comp. Bleed Valve Open	+70	+100	+145	+490
Exhaust Noz. Area Change +4%	-11	+130	+10	+380
-4%	+18	-180	-20	-50
Turb. Noz. Guide Vane Bow				
1st Turb. Area +4%	+11	+30	-74	+84
2nd Turb. Area +4%	+25	-77	+225	+218

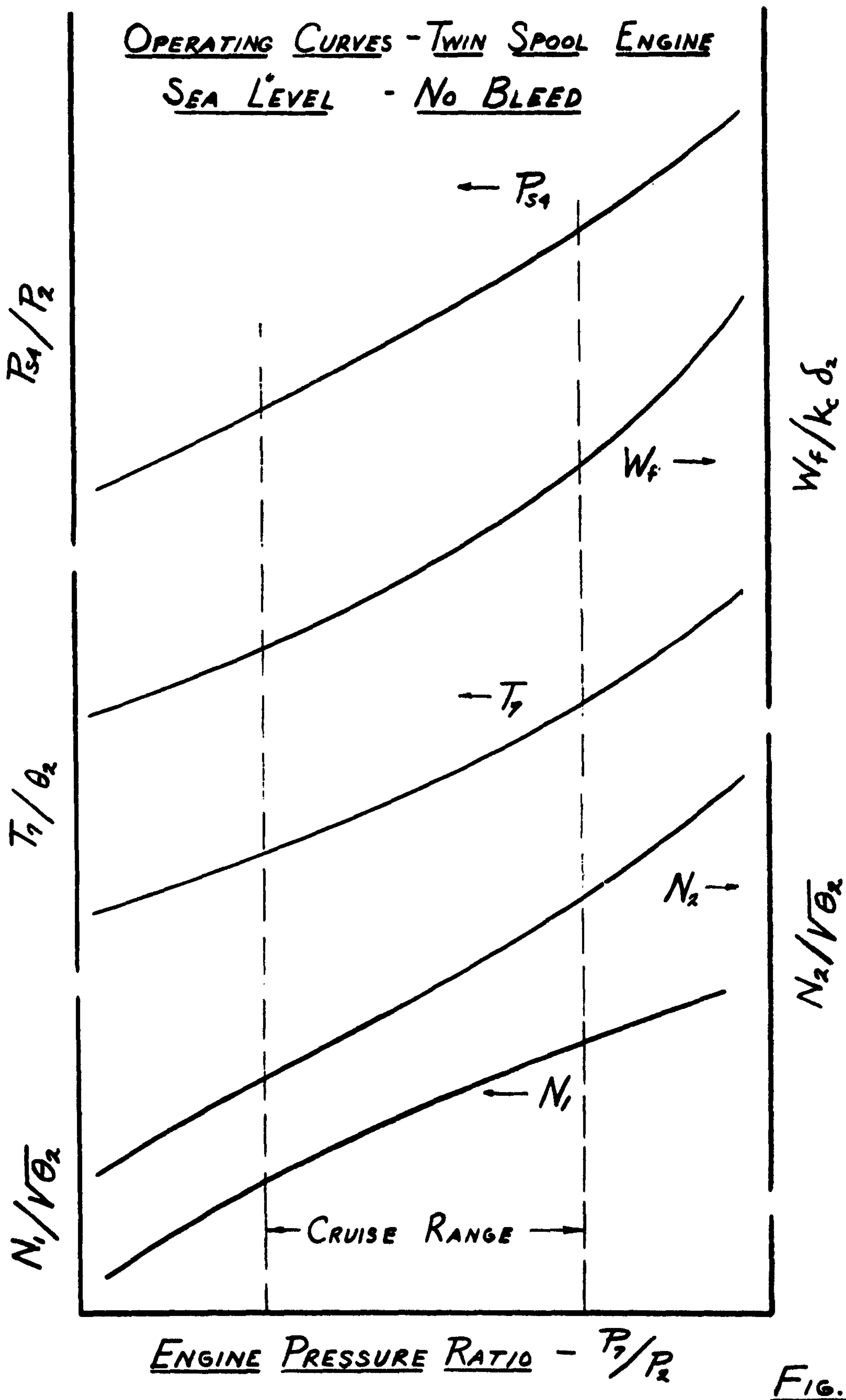
Simultaneously occurring deteriorations provide approximately algebraic addition of their effects on each parameter, thus if this condition exists, separation of the deteriorations is very difficult. However, there are no known combinations of deteriorations that will provide cancelling efforts on all of the parameters, thus the general condition of the engine is revealed through changes in the parameters.

2.1 Initial Engine Performance Curves

Initial engine performance curves are required to establish reference conditions to which changes in the measured values of the gas generator parameters can be related. This initial performance is established (preferably with the engine mounted in the airplane to account for any effects of aerodynamic obstructions, etc.) by operating at a series of values of pressure ratio in the cruise range of EPR and recording the values of the other gas generator parameters. The initial performance may be established for three different conditions: It may be established a) by running the engines in the airplane on the ground for values of EPR over the cruise range with all bleed extractions shut off, or b) with bleed extraction operating, or c) by taking the first ten flights and averaging the data to produce composite data with bleed and Reynolds' number effects factored in. This data is then plotted to provide curves of gas generator parameters versus EPR. Fig. 14 shows qualitatively this group of curves for case (a). Corrected parameters are used in these plots to make them applicable for non-standard temperature days. The corrected parameters are defined below.

$$N_1' = \frac{N_1}{\sqrt{\theta_2}}$$ - Corrected speed (low)

$$N_2' = \frac{N_2}{\sqrt{\theta_2}}$$ - Corrected speed (high)



OPERATING CURVES - TWIN SPOOL ENGINE
SEA LEVEL - NO BLEED
P_{S4}/P_2
$\leftarrow P_{S4}$
$W_f \rightarrow$
$W_f/K_c\,\delta_2$
$\leftarrow T_7$
T_7/θ_2
$N_2 \rightarrow$
$N_2/\sqrt{\theta_2}$
$\leftarrow N_1$
$N_1/\sqrt{\theta_2}$
← CRUISE RANGE →
ENGINE PRESSURE RATIO - P_7/P_2

FIG. 14

$W_f' = \dfrac{W_f}{k_c \delta_2}$ - Corrected fuel flow

$T_7' = \dfrac{T_7}{\theta_2}$ - Corrected turbine discharge temperature

$P_{s4}' = \dfrac{P_{s4}}{P_2}$ - Compressor discharge pressure ratio

k_c = Correction coefficient for T_2 - Supplied by engine manufacturer

When the initial curves of Fig. 14 are used with airborne recorded data, the standardized measured parameters must be corrected for Reynolds' number effects and bleed air, if bleed significantly confounds the data.

For ground test operations the curves of Fig. 14 are still applicable for reference. In this case tests will be conducted at a preselected value of EPR, and therefore, only one operational point will be used on each of the initial performance curves. This selected value of EPR is held constant and should be a value that is obtainable over a possible 0°F - 120°F ambient temperature range.

2.2 Reynolds' Number Correction

When engine performance data is obtained airborne and the processed results are to be compared to the initial performance characteristics, Reynolds' number corrections must be applied if meaningful interpretations in the data are to be made. These corrections can be applied to the standardized measured data or to the initial performance curves of Fig. 14. In the first and preferable

case, it is proposed that the Reynolds' number correction be an increment that is added or subtracted from the standardized value of the parameter as a function of the altitude at which that parameter was measured. This kind of engine data is furnished by the engine manufacturer and could be presented in graphical form similar to that shown in Fig. 15. The Reynolds' number effect corrections are:

$$(N_1')_{corr} = N_1' + \Delta N_1' \quad (109) \qquad (T_7')_{corr} = T_7' \pm \Delta T_7' \quad (112)$$

$$(N_2')_{corr} = N_2' + \Delta N_2 \quad (110) \qquad (P_{s4}')_{corr} = P_{s4}' + \Delta P_{s4}' \quad (113)$$

$$(W_f')_{corr} = W_f' + \Delta W_f' \quad (111)$$

2.3 Parameter Corrections for Bleed Air Extraction

When bleed air significantly affects the magnitudes of the gas generator parameters, corrections for bleed air extraction must be applied to the measured values before such values can be compared to the initial engine performance curves of Fig. 14. In flight bleed air will be extracted so this essentially means the measured gas generator parameters must be corrected back to no bleed conditions, because the curves of Fig. 14 were generated with bleed air shut off.

The following discussion illustrates the bleed air correction procedure that is followed and assumes that the percent bleed air ($\% \, W_b/W_a$) is inferred by a pressure measurement or is a known quantity supplied by the airframe manufacturer. For illustrative purposes the method of correction will be applied to a measured value of fuel flow.

Let

$(W_f')_m$ = the measured value of W_f' with bleed

$(W_f')_{corr}$ = the value of the measured value of fuel flow corrected back to the no bleed condition

Reynold's Number Correction Curves

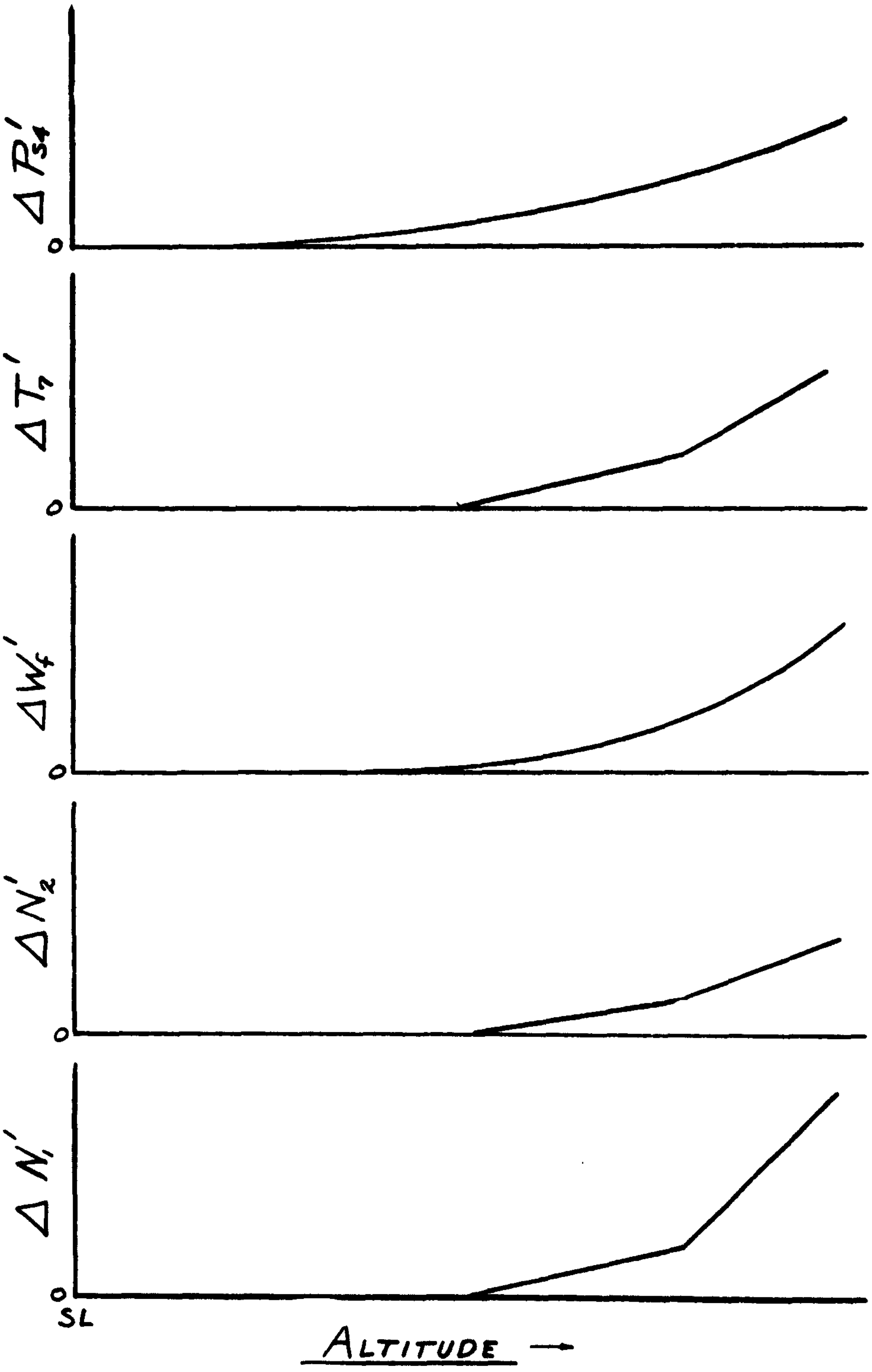


Fig. 15

$(\Delta W_f')_{HP}$ = change in W_f' for high pressure (H.P.) bleed extraction for a given measured value of P_3/P_2

$(\Delta W_f')_{LP}$ = change in W_f' for low pressure (L.P.) bleed extraction for the same measured P_3/P_2

The correction equation is defined as follows:

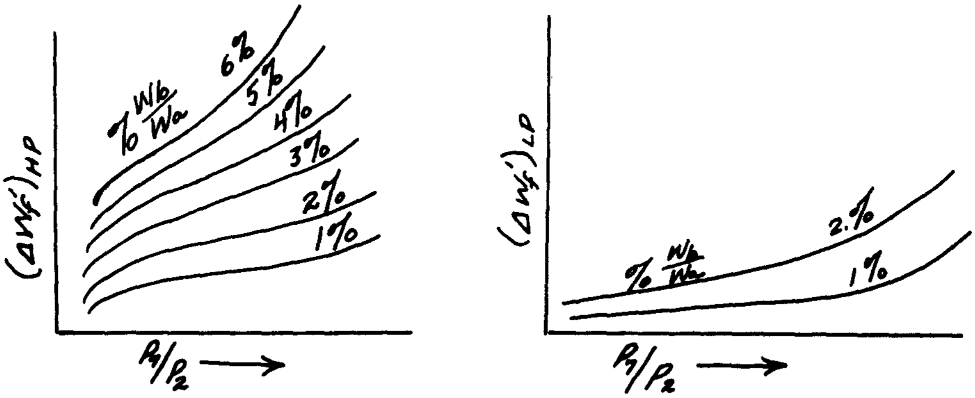
$$(W_f')_{corr} = (W_f')_m - \left[(\Delta W_f')_{HP} + (\Delta W_f')_{LP}\right] \qquad (114)$$

Here $(\Delta W_f')_{HP}$ and $(\Delta W_f')_{LP}$ are known functions of percent bleed air $(\% \, W_b/W_a)$ and pressure ratio P_3/P_2. That is:

$$(\Delta W_f')_{HP} = f\left[\%\left(\frac{W_b}{W_a}\right)_{HP}, \left(\frac{P_3}{P_2}\right)\right] \qquad (115)$$

$$(\Delta W_f')_{LP} = f\left[\%\left(\frac{W_b}{W_a}\right)_{LP}, \left(\frac{P_3}{P_2}\right)\right] \qquad (116)$$

The functions defined by Eqs. (115) and (116) are supplied by the engine manufacturer and may be in the form of 3-D curves similar to those shown in Figs. 16a and 16b.



(a) - High Pressure (b) - Low Pressure

Fig. 16 Est. Change in W_f' Due to Airbleed

In a similar manner the bleed correction equations for the other gas generator parameters would be:

$$(N_1')_{corr} = (N_1')_{meas} - [(\Delta N_1')_{HP} + (\Delta N_1')_{LP}] \qquad (117)$$
$$(N_2')_{corr} = (N_2')_{m} - [(\Delta N_2')_{HP} + (\Delta N_2')_{LP}] \qquad (118)$$
$$(T_7')_{corr} = (T_7')_{m} - [(\Delta T_7')_{HP} + (\Delta T_7')_{LP}] \qquad (119)$$
$$(P_{34}')_{corr} = (P_{34}')_{m} - [(\Delta P_{34}')_{HP} + (\Delta P_{34}')_{LP}] \qquad (120)$$
$$(P_7')_{corr} = (P_7')_{m} - [(\Delta P_7')_{HP} + (\Delta P_7')_{LP}] \qquad (121)$$

Also, the function curves for each of these gas generator parameters for high and low bleed extractions are needed to give the parameter changes in terms of % N_b/W_a and P_b/P_2 .

2.4 Analysis Procedure Summary

The following is a general summary of the steps necessary in the deterioration analysis of the twin spool engine using the generic performance data of Fig. 14 and airborne data acquisition.

a) Initially there will be available basic performance data on a new engine-airframe combination. This will consist of:

1. A set of corrected gas generator parameter versus pressure ratio performance curves on a new engine mounted in the airframe and tested at S.L.S. conditions with no bleed extraction. These curves to be similar to those of Fig. 14.

2. A set of Reynolds' number correction curves similar to Fig. 13 to correct the airborne measured values of the gas generator parameters for Reynolds' number effects. These curves will supply the incremental corrections called for in Eqs. (109) through (113).

3. A set of curves for each gas generator parameter that provides both high pressure (H.P.) and low pressure (L.P.) parameter changes as a function of percent bleed air $\% \frac{W_b}{W_a}$ and EPR. These curves, or functions, are to be used to correct the airborne, measured gas generator parameters back to the no bleed condition to make the data compatible with the initial performance parameters to which they will be compared. The bleed correction equations are (114) and (117) through (121).

b) Obtain data at stabilized flight conditions within the cruise range of EPR. Automatically acquire 25 sets of data about every 2 hours or once a flight, whichever is shorter. A set of data consists of the parameters listed in Table 14. The 25 sets of data are obtained in rapid sequence.

c) Average the 25 values of each measurement. This calculation is performed in a ground based computer.

d) Correct the average value of the measurements to standard ambient conditions. Corrected parameter expressions are those listed in 2.1.

e) Apply Reynolds' number corrections to averaged correction data taken above 30,000 feet altitude as outlined in 2.2.

f) Apply bleed air corrections to averaged corrected data of (d) or (e) as outlined in 2.3.

g) Subtract a value of the corrected parameter, obtained from the curves of Fig. 14 at the average pressure ratio of (c), from the overall corrected parameter of (f). This difference is a measure of engine deterioration.

h) Calculate the log average of the deteriorations obtained in (g). Use the smoothing equation defined in Section 2.5.

i) Plot the log average of each deterioration vs. time and compare to limits on the parameters.

Appendix II
Lubrication System Analysis

The lubrication system is a subsystem that historically has been troublesome in all engines. The problems are mainly in the form of leaks or contamination that reduces oil flow to the required areas and problems with the venting and oil seal pressurization. The faults are usually detected by visual observation of external oil leaks, excessive oil consumption, and changes or fluctuation in oil pressure.

Two different lubrication systems are in common use. One system uses a pressure regulator to maintain an essentially constant pressure on the oil distribution system. The second system does not regulate the pressure except as a safety precaution at extreme overpressures. The methods of providing early warning of distress in these two systems necessarily differ in detailed implementation, although the fundamental concepts used are the same.

Basically, the flow pressure relationship in an hydraulic system is established by the characteristics of the fluid (density, viscosity, etc) and the resistance of the piping systems. It is this flow pressure relation that is used to detect changes in lube system performance that are indicative of distress. For instance, plugging a discharge nozzle results in an increased resistance to flow. In a regulated pressure systemthis increased resistance will be translated into a decreased flow, while in an unregulated pressure system, it will be translated into an increased pressure.

1 Unregulated Pressure System

In the unregulated pressure system, a constant displacement, engine driven pump supplies oil to the distribution piping system. The quantity of oil supplied is directly proportional to engine speed, thus the oil pressure will

be a function of engine speed. The characteristics of the oil (ie, viscosity, density, etc.) are related to the oil temperature, thus the pressure will be a function of oil temperature. Standardizing or correcting the measured oil pressure to a reference engine speed and oil temperature provides a reference pressure that is dependent only upon the distribution system and pump characteristics and thus can be used to detect changes in these components that are indicative of trouble.

The following is a derivation of the corrected oil pressure equation from simple concepts. The assumptions made in this derivation are that: a) the entire oil system is analogous to an effective composite orifice or nozzle which offers the primary resistance to oil flow and the piping system losses are negligible in comparison, b) temperature effects are reflected in an oil density change and over the range of temperatures experienced the density decreases linearly as temperature increases, c) total oil flow to this composite orifice is directly proportional to pump speed and hence engine speed, N.

For these assumptions the pressure drop across the orifice is:

$$\Delta P = \frac{\rho \mathcal{g}^2}{2A^2} \tag{122}$$

where ρ = density

$\mathcal{g}$ = oil flow

A = effective orifice cross section

As a function of temperature the oil density is:

$$\rho = \rho_o \left[1 + \beta(T_o - T)\right] \tag{123}$$

where ρ_o = density at temperature T_o

T_o = reference temperature of oil

β = temperature coefficient of density

And the oil flow as a function of pump speed is:

$$g = kN \tag{124}$$

where N = engine speed

k = proportionality constant

Substitute (123) and (124) into (122) letting also

$$\Delta P = P = \text{gauge pressure}$$

$$P = CN^2\left[1+\beta(T_o - T)\right] \tag{125}$$

where

$$C = \frac{k^2 \rho_o}{2A^2} \tag{126}$$

At a reference operating point, $T = T_o$, $P = P_o$ and $N = N_o$, Eq. (125) becomes:

$$P_o = CN_o^2 \tag{127}$$

Similarly, at some other operating point $T = T_m$, $P = P_m$ and $N = N_m$, where the subscript (m) represents a measured quantity, Eq. (125) can be written:

$$P_m = CN_m^2\left[1+\beta(T_o - T_m)\right] \tag{128}$$

Now divide (128) by (127)

$$P_m = P_o\left(\frac{N_m}{N_o}\right)^2\left[1+\beta(T_o - T_m)\right] \tag{129}$$

Finally, if P_o be considered the corrected value of pressure (P_c) as temperature and speed changes, referred to the initial conditions of temperature, pressure and speed, then

$$P_c = P_m\left(\frac{N_o}{N_m}\right)^2\left[\frac{1}{1+\beta(T_o - T_m)}\right] \tag{130}$$

For the unregulated pressure system, the following measurements should be made:

1. Pm Oil Pressure

2. Tm Pump inlet oil temperature

3. N_m Engine Speed (meas. for other purposes)

4. Oil Sump Pressure

5. Oil Tank Pressure

6. Oil Consumption

Measurements 1, 2, and 3 are used to calculate the corrected oil pressure P_c from equation (130) for trend analysis of the system. Increasing corrected pressure in general means lines or nozzles are plugging. The smallest nozzle in the unregulated system discharges about 10% of the total flow. If this nozzle were plugged the pressure would increase about 5% (eq. 122), hence a measure of oil pressure repeatable to within 2% should detect the equivalent of partial plugging of the smallest nozzle.

In general cracks or leaks will show as oil loss through measurement (6) before they will be detected as pressure changes, although large leaks are detectable by decreased pressure, the opposite manifistation from plugging.

Measurements (4) and (5) are used to detect seal leaks, vent line restrictions, unproper vent valve operation etc.

2 Regulated Pressure Lubrication System

In the regulated pressure lubrication system, a constant displacement, engine driven pump provides oil to the piping system through a pressure regulator that bleeds some of the discharge oil back to the pump inlet to maintain constant pressure on the distribution system. In this system, the oil pressure is indicative of the pressure regulator performance, and to infer lube system condition requires the measurement of oil flow. The oil flow is a function of the pressure (which is regulated), and the oil characteristics (density viscosity etc.) which are dependent upon temperature. Thus the oil flow is a function of

pressure and temperature. Standardizing or correcting the measured oil flow for pressure and temperature provides a reference that is dependent only upon the lubrication distribution system and thus can be used to detect changes in it that are indicative of trouble.

The following is a derivation of the corrected oil flow equation using essentially the same approach and assumptions set forth in par. 1. Correspondingly, Eqs. (122) and (123) are valid and (124) is not needed because the flow (g) is to be measured.

Substitute (123) into (122) and solve for g, where again

$\Delta P = P =$ (gauge pressure).

$$g = K\sqrt{\frac{P}{1+\beta(T_0-T)}} \tag{131}$$

where

$$K = \sqrt{\frac{2A^2}{\rho_0}} \tag{132}$$

At a reference operating point where $T = T_0$, $P = P_0$ and $g = g_0$,

Eq. (131) becomes

$$g_0 = K\sqrt{P_0} \tag{133}$$

Now at some other operating point $T = T_m$, $P = P_m$ and $g = g_m$, where the subscript (m) represents a measured quantity, Eq. (131) can be written:

$$g_m = K\sqrt{\frac{P_m}{1+\beta(T_0-T_m)}} \tag{134}$$

Divide (134) by (133)

$$g_m = g_0\sqrt{\left(\frac{P_m}{P_0}\right)\left(\frac{1}{1+\beta(T_0-T_m)}\right)} \tag{135}$$

Now, if g_0 be considered the corrected value of flow (g_c) as temperature and pressure changes, then,

$$g_c = g_m\sqrt{\left(\frac{P_0}{P_m}\right)\left(1+\beta[T_0-T_m]\right)} \tag{136}$$

If the pressure regulator were perfect, that is maintained an absolutely constant pressure then the term Po/Pm would always be 1.0. However, the pressure regulators require some change in pressure to re-apportion the flow between the lube system and the by-pass, hence for a system in which trouble is occurring, Po/Pm will seldom be 1.0. This change in oil pressure has been used to infer lube system problems. It should not be as sensitive a measure as the corrected oil flow measurement proposed.

For the pressure regulated system, the following measurements should be made.

1. Pm Oil pressure
2. T_m Pump inlet oil temperature
3. g_m Oil flow
4. Breather pressure differential
5. Scavenge oil back pressure
6. Oil Consumption

Measurements 1, 2, and 3 are used to establish the corrected oil flow from equation 136 for trend analysis of the system. Decreasing corrected oil flow in general means lines or nozzles are plugging. The smallest nozzle in the regulated pressure lube system discharges about 4% of the total flow. If this nozzle were plugged the flow would decrease by this amount, hence a measure of the oil flow repeatable within 2% should detect the equivalent of partial plugging of the smallest nozzle.

As in the unregulated system, cracks or leaks will generally show as oil loss through measurement (6) before they will be detected by pressure or flow measurements, although large leaks will be detected by measured flow, the opposite manifestation from plugging.

Measurements (4) and (5) are used to detect seal leaks, vent line restriction, improper vent valve operation, etc.

APPENDIX III

ANALYZER ACCURACY

This Appendix outlines the methods and data used in estimating the analyzer accuracy.

1 Analyzer Accuracy Criterion

Analyzer accuracy is the ability of the analyzer to distinguish between engines that are operating within the limits of acceptable change of the degradation parameters and those which have changed more than this allowable limit. An analyzer error is an erroneous indication in which the engine is shown to be outside of an acceptable limit (i.e. bad) when it is really inside the limit (i.e. good) or vice-versa. The criterion of accuracy used in this analysis is the probable or, mean number of tests between erroneous indications. This is analogous to the "mean time between failure" criterion in reliability analysis.

The "errors" or erroneous indications arise because the measurement and computation of the deterioration parameters is not perfect, thus repeated measurements will not be exactly the same even if the item being measured has not in fact changed. If this variation of the measurements is small compared to the allowable limit, then an accurate analyzer is obtained. If however this variation in measurement is large compared to the albwable limit, then many of the measurements will indicate the engine is outside of the limit when in fact, it is not, i.e. an inaccurate analyzer.

An index of accuracy of a measurement that is made for comparison against a limit is the ratio of the limit to the standard deviation of the measurement. Referring to Fig. 17 the familiar bell shaped curve represents the normal distribution of measurements. The most probable value of the parameter is the mean value of all of the measurements. The probability that any single measurement will lie outside a predetermined limit is the ratio of the shaded area under the probability curve to the total area under the curve. Values of this ratio are tabulated in many texts on statistics and have been used to define the probability that a single reading of a deterioration parameter will be inside or outside of the allowable limits. Curves showing the frequency of erroneous readings are given in Fig. 18 for the condition of a new engine (i.e. no deterioration) for a 50% degraded engine (i.e. engine performance changed by half of the allowable limit) and for 75% deteriorated engine. These curves can be used to determine the probable number of readings that will be made before an erroneous indication is obtained. To use the curves it is necessary to know the standard deviations of the measurements, the limits, and the deterioration.

2 Standard Deviations of Measurements

Measurement components in general exhibit three basic types of errors.

1. Fixed or permanent errors
2. Semi-permanent errors
3. Random errors

Illustrative Error Distribution Curve with Limits

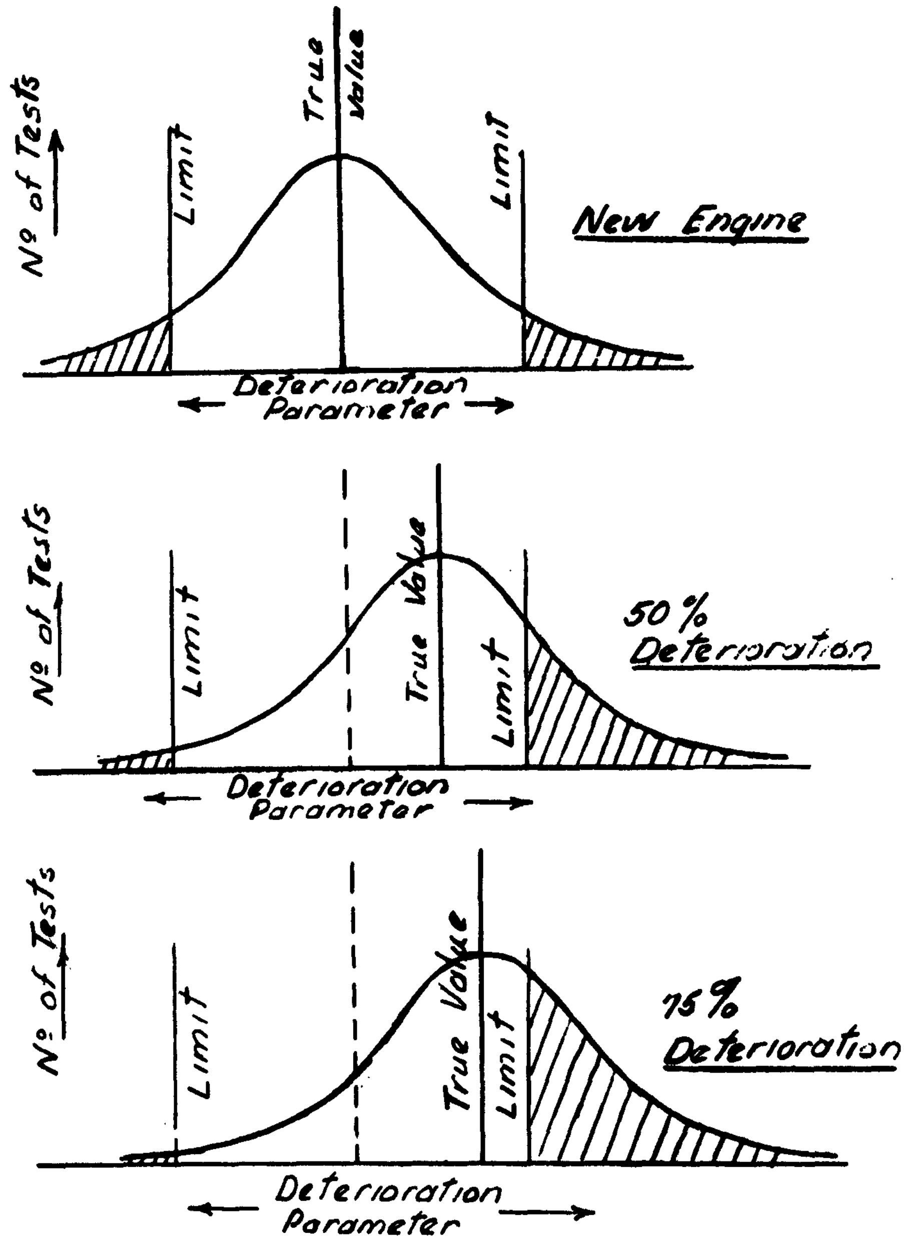


Fig. 17

Tests per Bad Indication Versus L/σ

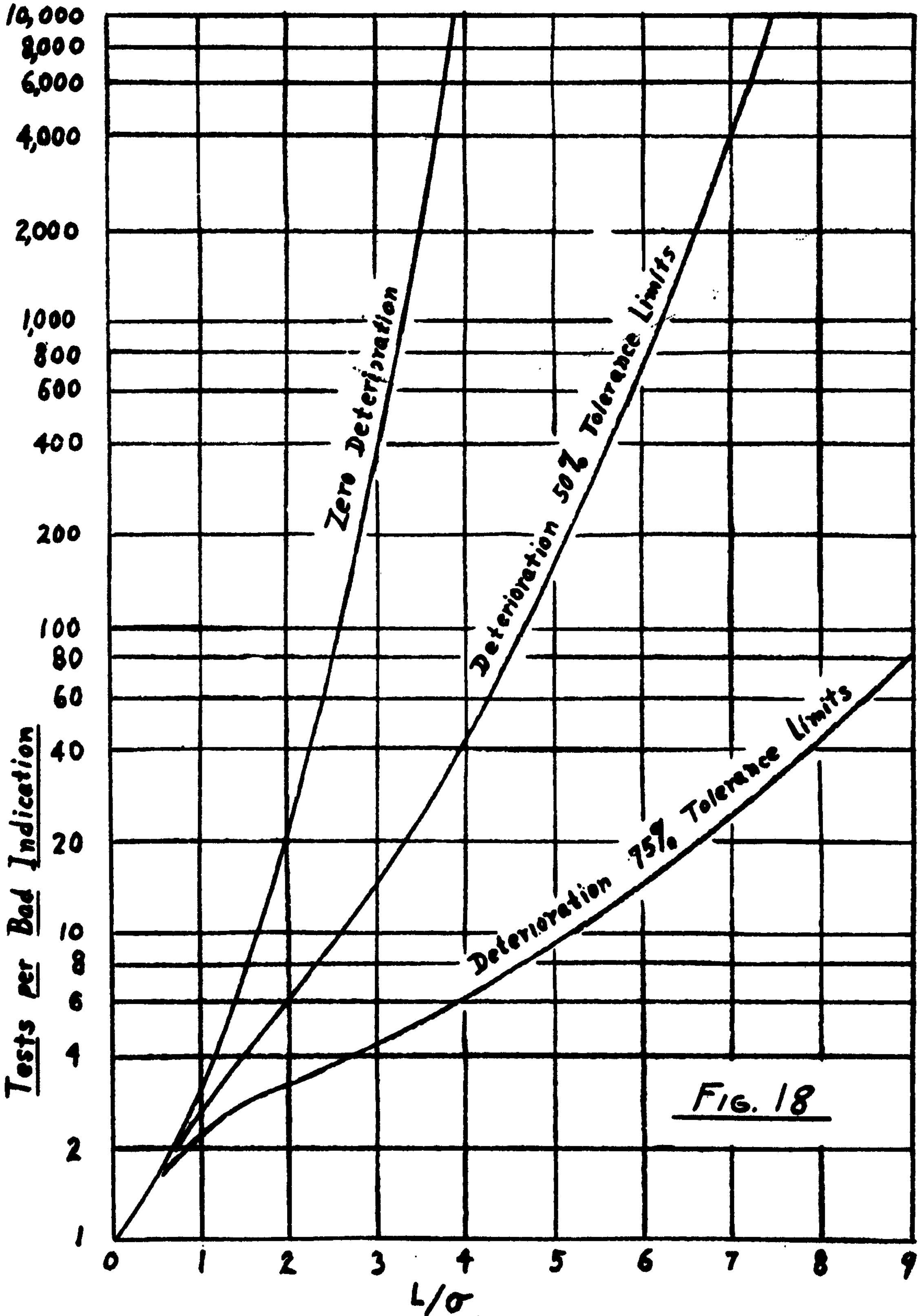


FIG. 18

Fixed or permanent errors arise through such sources as initial calibration error, component non-linear characteristic, drift or ageing, etc. These errors cannot be reduced by averaging repeated readings or any other statistical technique. In comparing successive readings of a measurement system, these errors do not affect the comparison, provided the measurement system is operated always at the same point. If different operating points, or different measurement systems are used, these errors will appear. For the accuracy analysis subsequently presented, the conservative approach has been taken and these errors have been included at full value.

Semi-permanent errors arise mainly through environmental changes such as temperature, acceleration, etc. These errors can in general be reduced by averaging, if the causative effects are randomly distributed in time and a sufficiently long test is made to average the contributing sources.

Random errors arise from such items as friction, readout resolution, parallax, etc. These errors can be reduced to an unlimited extent by averaging enough readings.

For the accuracy analysis subsequently presented, the semi-permanent, and random errors have been included at full value for those procedures where only single readings of the measurements are made. For those procedures where multiple readings of the measurements are made and averaged to obtain a single value for comparison the semi-permanent and random error variances have been taken as 60% of the single reading variances. For those procedures where multiple readings of the measurements are averaged with a variation of ambient conditions, the semi-permanent error

variances were taken as 30% of the single reading variance.

The variance of a measurement is defined as the standard deviation squared, and the total variance of a computation or measurement can be calculated from the variances of all items making it up. The methods of combining variances are described in any text on statistics. Table 20 below lists the values of the variances used in making the analyzer accuracy estimates shown subsequently. These variances represent our best estimates of the performance of high quality aircraft instruments and recording systems.

<u>Table 20</u>

<u>Measurement Variances</u>

Physical Quantity	Variance (% of point)^2			
	Ground Based Measurements		Airborne Measurements	
	Manual Data Acquisition	Automatic Data Acquisition	Manual Data Acquisition	Automatic Data Acquisition
P_2	.50	.50	2.00	.80
T_2	.50	.40	.50	.23
W_f	1.30	1.00	1.30	.55
T_5	.50	.40	.50	.23
N	.32	.11	.32	.06
$P_{32} \backslash P_2$	1.00	.80	1.00	.45
P_5/P_2	1.00	.80	1.00	.45
Corrected Parameters				
T/θ	1.00	.80	1.00	.46
$N/\sqrt{\theta}$	.44	.21	.44	.12
$W_f/\delta\theta^n$	1.92	1.58	3.42	1.41

3 Deterioration Parameter Limits

The deterioration parameters are the combination of measurements and computations which are taken as criteria of engine performance. A deterioration requiring maintenance action is implied when any deterioration parameter appreciably exceeds the tolerance limits.

3.1 Single Spool Deterioration Limits

For the single spool engines the deterioration parameters are the compressor efficiency function, the burner efficiency, and the turbine efficiency. The derivation and calculation of these parameters are described in a previous section of this report. The tolerance limits on these parameters are based on whicever of the following criteria occur first as the deterioration progresses.

1. Thrust loss of 10%
2. Specific Fuel Consumption increase of 10%
3. Burner Temperature Increase of 45° at Military Operations
4. Compressor Stall

Functional relationships between these characteristics and the deterioration parameters were determined from a mathematical model of the J-79 engine. These functions are not amenable to simple analytical expressions but numerical values can be calculated over the operating range. Numerical correlations of the changes required in each parameter to cause one of the above four characteristics to reach its limit were used to establish the deterioration parameter limits. These limits are listed in the following table.

Table 21

Single Spool Engine Deterioration Limits

Deterioration Parameter	Limit	Reason For Limit	Temp. Diff. Limit
Compressor	2%	Stall	10.7%
Turbine	5%	SFC	7.2%
Combustor	10%	SFC	5.6%

3.2 Twin Spool Deterioration Limits

The deterioration parameters for the twin spool engine are the gas generator characteristics of rotor speed, fuel flow, and EGT plotted against engine pressure ratio. The limit of these parameters used in estimating the accuracy of the engine analyzer were derived largely from the recommendations of Pratt & Whitney Aircraft, verified wherever possible by commercial airline experience. The table below lists the values of the limits used in making the accuracy estimates.

Table 22

Twin Spool Engine Deterioration Limits

Deterioration Parameter	Symbol & Unit	Limit
Rotor Speed	N_1' - RPM	$\pm$ 2%
Rotor Speed	N_2' - RPM	$\pm$ 2%
Fuel Flow	W_f' - lbs/hr	$\pm$ 4%
Exh. Gas Temp.	T_7' - Deg R	$\pm$ 3%

.4 Analyzer Accuracy Estimates

The estimates of the analyzer accuracy (i.e., the probable number of engine evaluations before obtaining an erroneous indication) were made using the curves of 1, the limits of 3, and the measurement accuracies of 2. The individual measurement accuracies were combined according to the appropriate functional

relations to obtain a total variance of the deterioration parameter. This total variance was then used to determine the ratio of L/σ which permits estimation of the probability of an erroneous indication.

4.1 Deterioration Parameter Variance (Single Spool Engine)

The equations for the total variance of the deterioration parameters for the single spool engine are:

$$V_{\eta_c} = 1.1\left[\left(\frac{\partial T_c}{\partial N'}\right)^2 V_{N'} + \left(\frac{\partial T_c}{\partial P_3'}\right)^2 V_{P_3'} + V_{T_m}\right] \tag{137}$$

$$V_{\eta_t} = 1.1\left\{\left[\frac{\partial\left(T_t - \frac{A_1}{C_1}T_c\right)}{\partial N'}\right]^2 V_{N'} + \left(\frac{\partial T_t}{\partial P_5'}\right) V_{P_5'} + \left(\frac{B_1}{C_1}\frac{\partial T_c}{\partial P_3'}\right)^2 V_{P_3'} + \left(1 - \frac{A_1}{C_1}\right)^2 V_{T_m}\right\} \tag{138}$$

$$V_{\eta_b} = 1.1\left\{\left[\frac{\partial\left(T_B - \frac{B_1}{C_1}T_c\right)}{\partial N_1'}\right]^2 V_{N'} + \left(\frac{\partial T_B}{\partial w_f'}\right)^2 V_{w_f} + \left(\frac{B_1}{C_1}\frac{\partial T_c}{\partial P_3'}\right)^2 V_{P_3'} + \left(1 - \frac{B_1}{C_1}\right)^2 V_{T_m}\right\} \tag{139}$$

Evaluation of these equations was done by evaluating the partials and constants using the mathematical model of the J-79 engine, and substituting the values in the above equations.

The estimates probable number of evaluations before obtaining an erroneous indication at three levels of engine deterioration are given in Tables 10 & 11, Sec. 2.5.1.

4.2 <u>Deterioration Parameter Variance</u> (Twin Spool Engines)

The equations for the deterioration parameters for the twin spool engines are:

$$V_{t\,N'} = V_{N'} + \left(\frac{\partial N'}{\partial EPR}\right)^2 V_{EPR}$$

$$V_{t\,w_f'} = V_{w_f'} + \left(\frac{\partial w_f'}{\partial EPR}\right)^2 V_{EPR}$$

$$V_{t\,T_7'} = V_{T_7'} + \left(\frac{\partial T_7'}{\partial EPR}\right)^2 V_{EPR}$$

Evaluation of these equations was done by evaluating the partials at a point in the cruise range from published data on several twin spool engine models and averaging the values of the partials for substitution.

The estimated probable number of engine condition determinations before obtaining an erroneous indication are given in Table 10 & 11 Sec. 2.5.1.

Aeronautical Systems Division, Dir/Aerospace Ground Equipment Engineering, Wright-Patterson AFB, Ohio.
Rpt Nr ASD-TDR-62-975, TURBOJET ENGINE ANALYZER DESIGN STUDY. Final report, Apr 63, 153p. incl illus., tables, 29 refs.

Unclassified Report

This report outlines methods of determining the condition of jet engines through measurement of performance sensitive parameters. The measurements required, test procedures, data processing, interpretation of results, and tentative limits are proposed. Estimates of the accuracy of the condition assessment,

(over)

limiting conditions and measurement accuracies are included.

The "state-of-the-art" in engine condition determination through nonperformance sensitive parameters is reviewed and programs for advancing it are proposed.

1. Turbojet engine analyzers
2. Feasibility and approaches to turbojet analysis
3. Turbojet engine performance techniques

I. AFSC Project 3147, Task 314702
II. Contract AF 33(616)-8508
III. General Electric Instrument Dept., West Lynn, Mass.
IV. M. E. Douglass et al
V. Not aval fr OTS
VI. In ASTIA collection

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